Short-Range Nuclear Structure

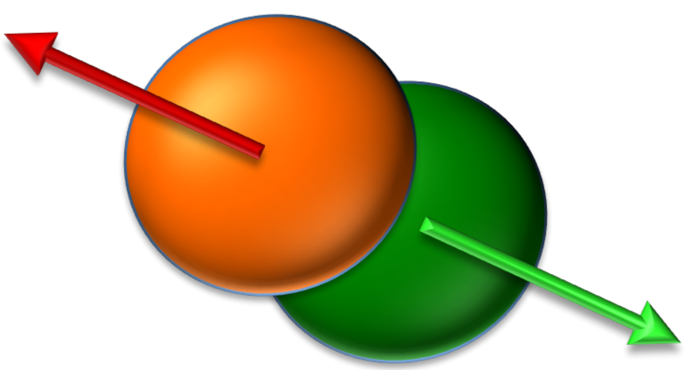
Or Hen – MIT

POETIC, November 15th 2016

SRC 101

SRC are pairs of nucleon that are close together in the nucleus (wave functions overlap)

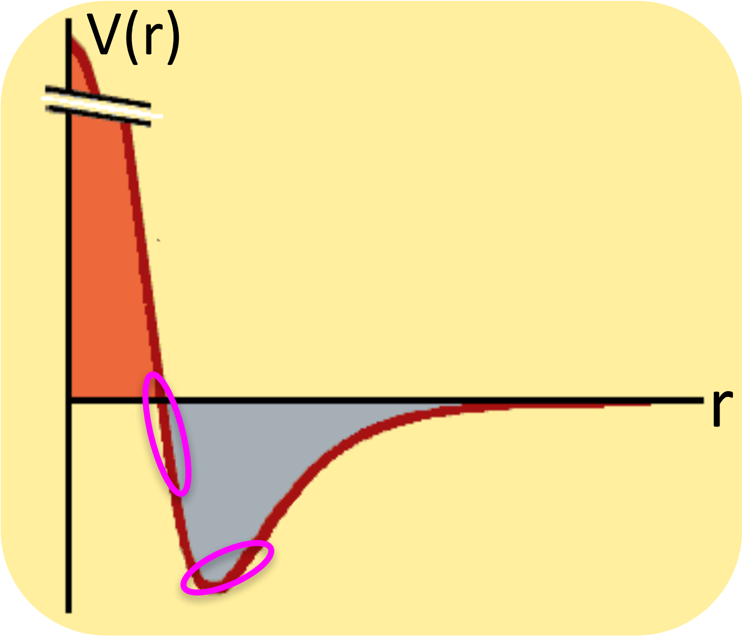
=> Momentum space: pairs with *high relative momentum* and *low c.m. momentum* compared to the Fermi momentum (k_F)



Why SRC?

Nuclear Physics

Better understanding of the *<u>nucleon-nucleon interaction</u>* and the nuclear momentum distribution



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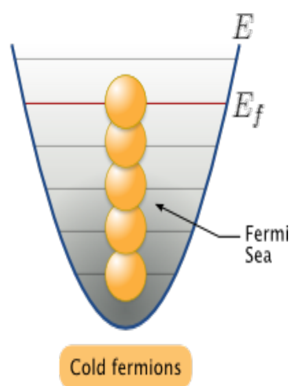

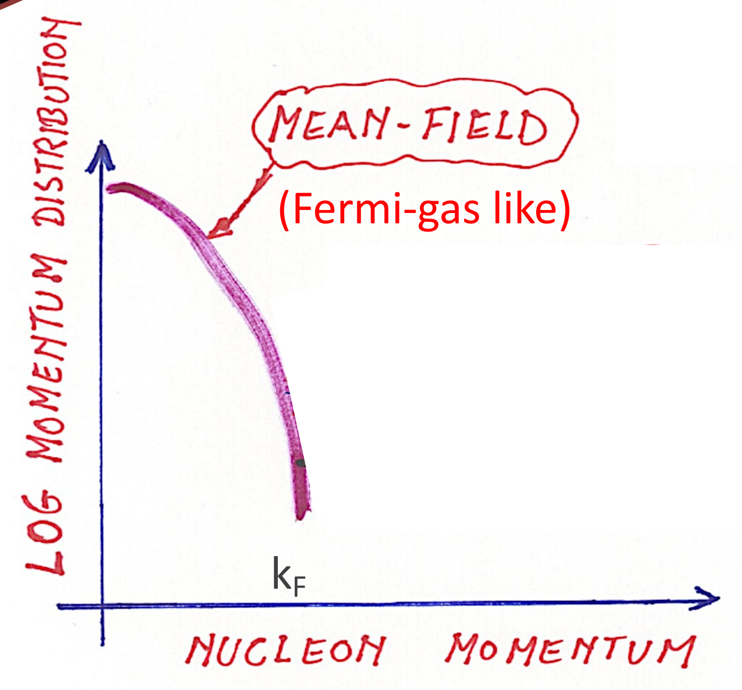

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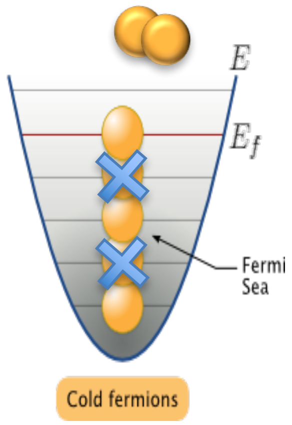
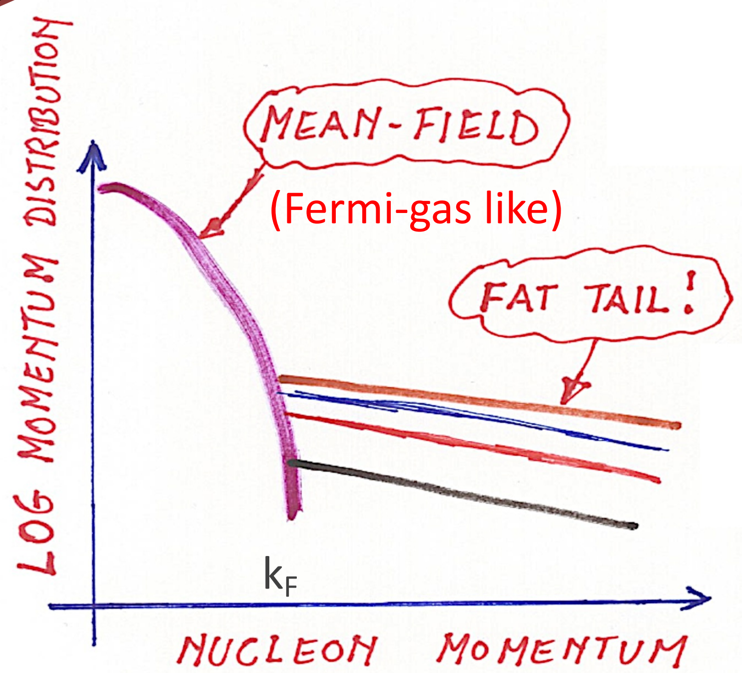




Why SRC?

You can’t do nuclei without correlations!

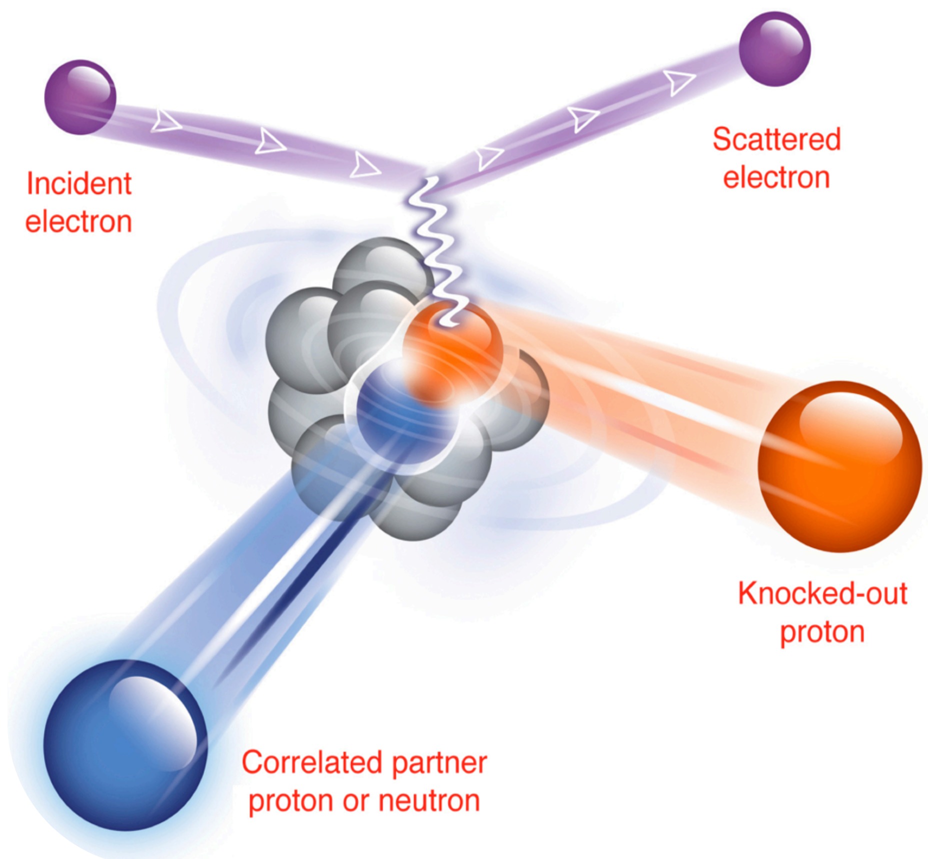
Why SRC?

Today: (short) overview of SRC and a presentation of a new effective theory for SRC in nuclei

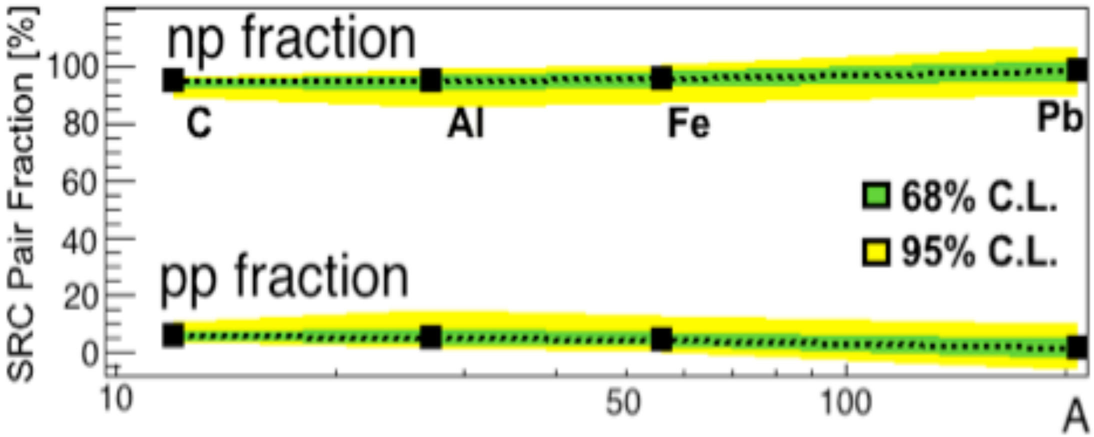
You can't do nuclei without correlations!

Exclusive 2N-SRC Studies

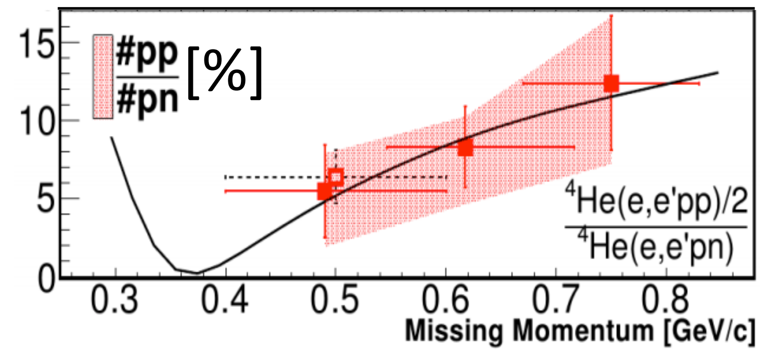
Breakup the pair =>
Detect both nucleons =>
Reconstruct ‘initial’ state



SRC Isospin Structure

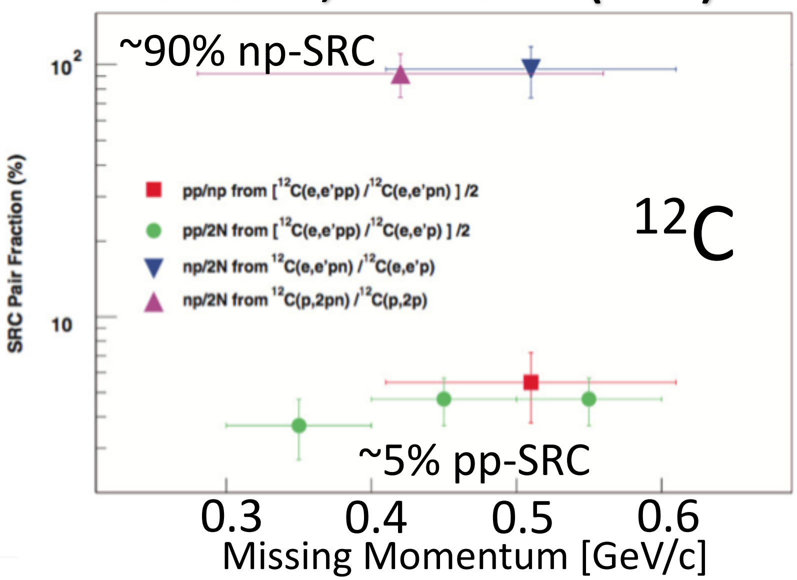


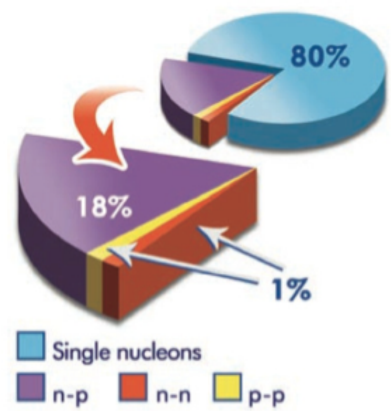
O. Hen et al., Science 364 (2014) 614

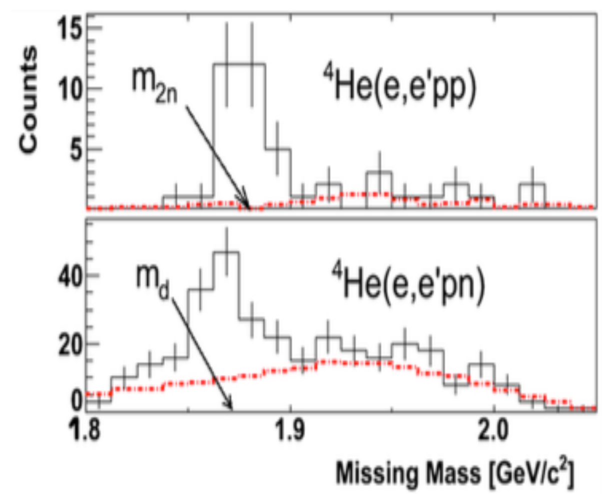


R. Subedi et al., Science 320 (2008) 1476

I. Korover et al., PRL 113 (2014) 022501







A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

SRC Isospin Structure

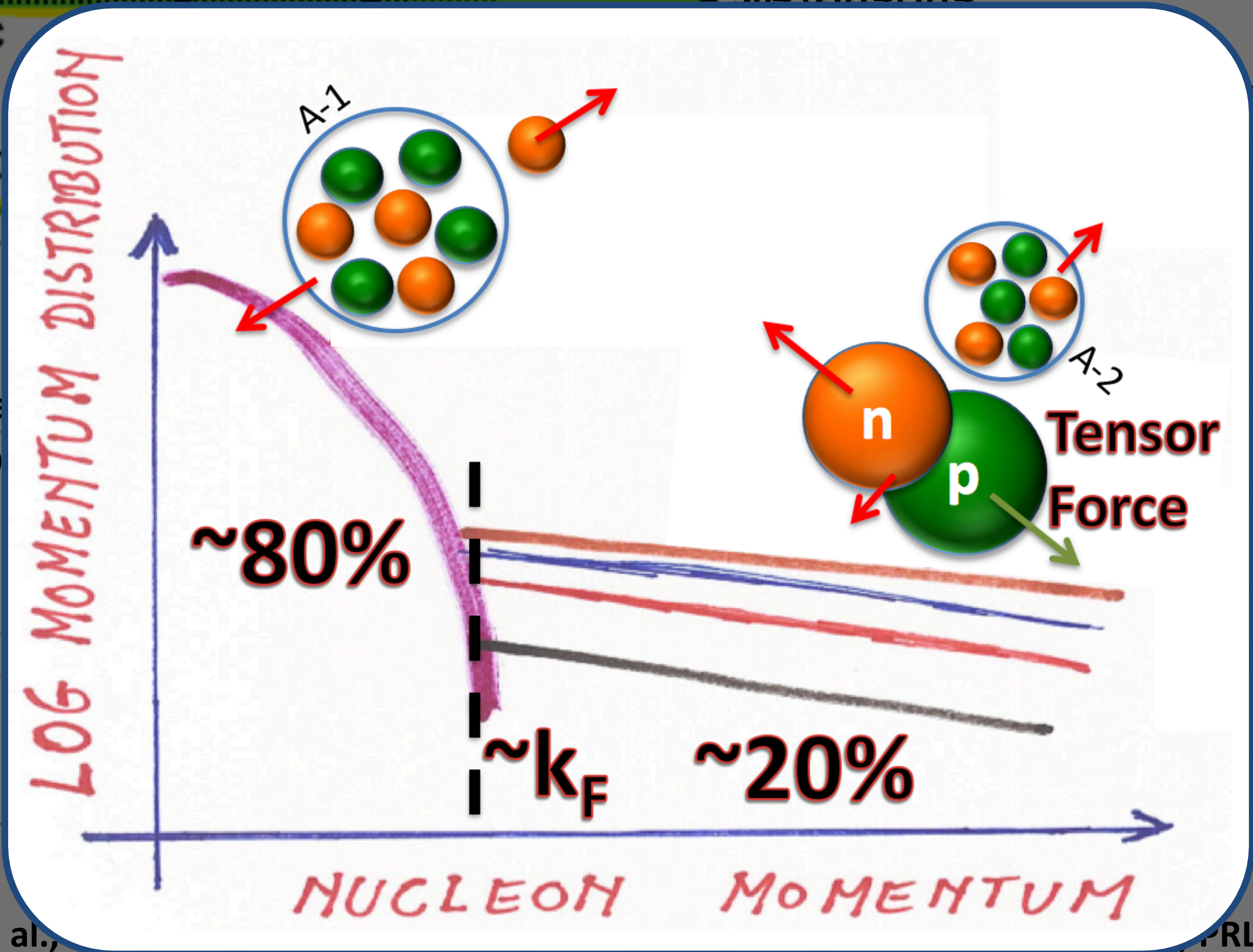
Bottom Line:

- SRCs account for:
  - ~ 20% of the nucleons in nuclei.
  - ~100% of the high-p ($k>k_F$) nucleons in nuclei.
- Predominantly due to np-SRC.
- Universal for A = 4 – 208 nuclei.
- **Tensor force** dominance at short distance.

0.3 0.4 0.5 0.6
Missing Momentum [GeV/c]

A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

Universal structure of nuclear momentum distributions



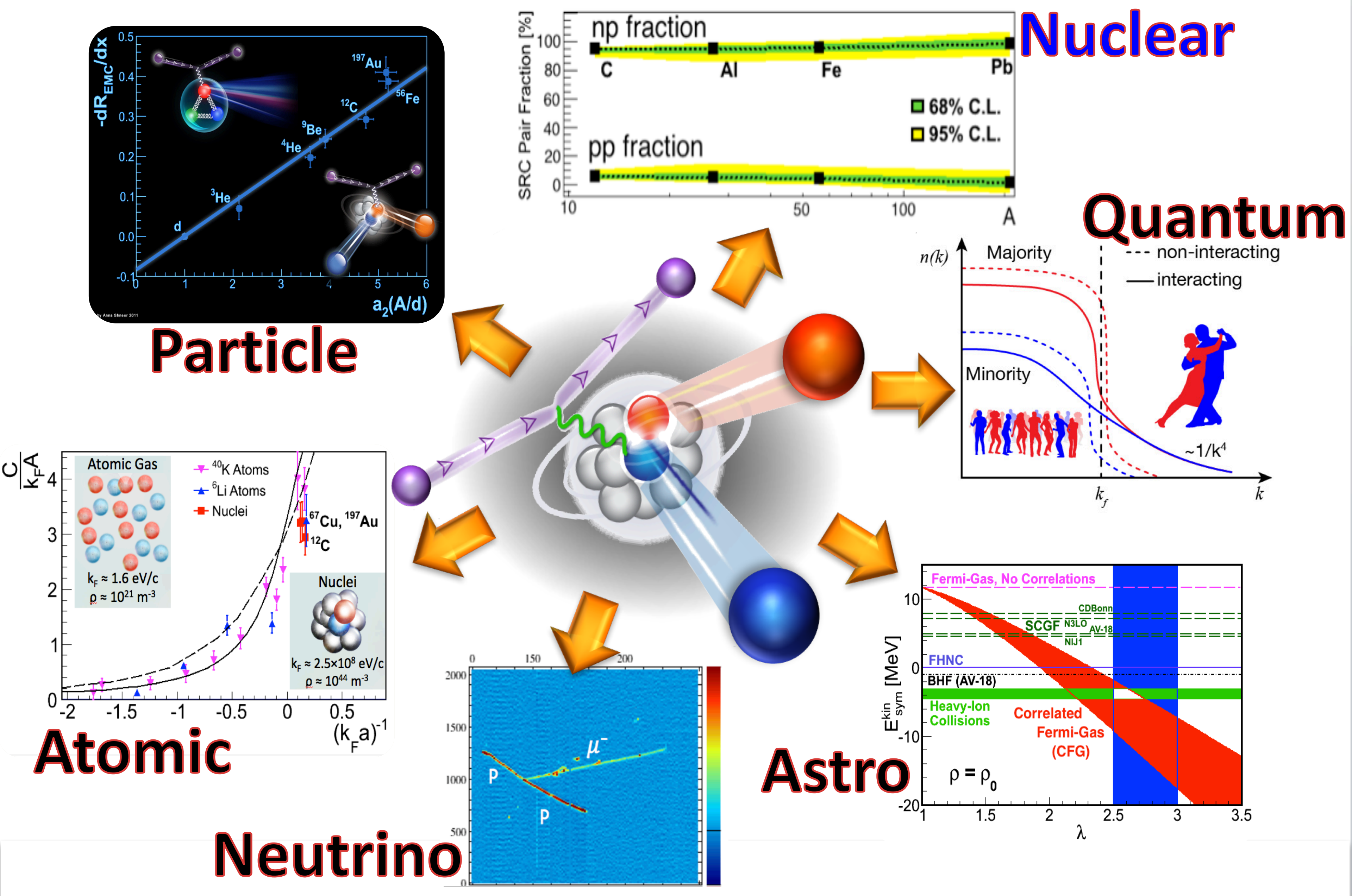
R. Sube

A. Tang et al.,

022501

PRL (2007)

Importance of SRC Properties



Two-component interacting Fermi systems

The contact term

Please forget about nuclear physics for a moment

The Contact and Universal Relations

Concept developed for dilute two-component Fermi systems with a short-range (δ-like) interaction.

$$\text{dilute} \equiv r_{eff} << a, d$$

Dilute System

Concept developed for dilute two-component Fermi systems with a short-range (δ-like) interaction.

$$\text{dilute} \equiv r_{eff} << a, d$$

Range of interaction

Scattering length

Distance between fermions

Range of interaction much smaller than the other relevant length scales in the problem

Dilute System

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

The Contact and Universal Relations

Contact interaction is represented through a boundary condition

Imposing this B.C. on the Schrödinger equation yields an asymptotic wave function when two fermions get very close

$$\Psi \xrightarrow[r_{ij}\to 0]{} \underbrace{(1/r_{ij} - 1/a)}_{\text{Two Body}} \underbrace{A_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})}_{\text{A-2}}$$

Dilute System → **Short Distance Factorization**

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

The Contact and Universal Relations

$$\Psi \xrightarrow[r_{ij}\to 0]{} (1/r_{ij} - 1/a) A_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})$$

$$n(k) = C / k^4 \quad \text{for} \quad k > k_F$$

Dilute System → Short Distance Factorization → **High Momentum Tail**

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<u>Tan's Contact term:</u>

1. Measures the number of SRC different fermion pairs.
2. Determines the thermodynamics through a series of universal relations.

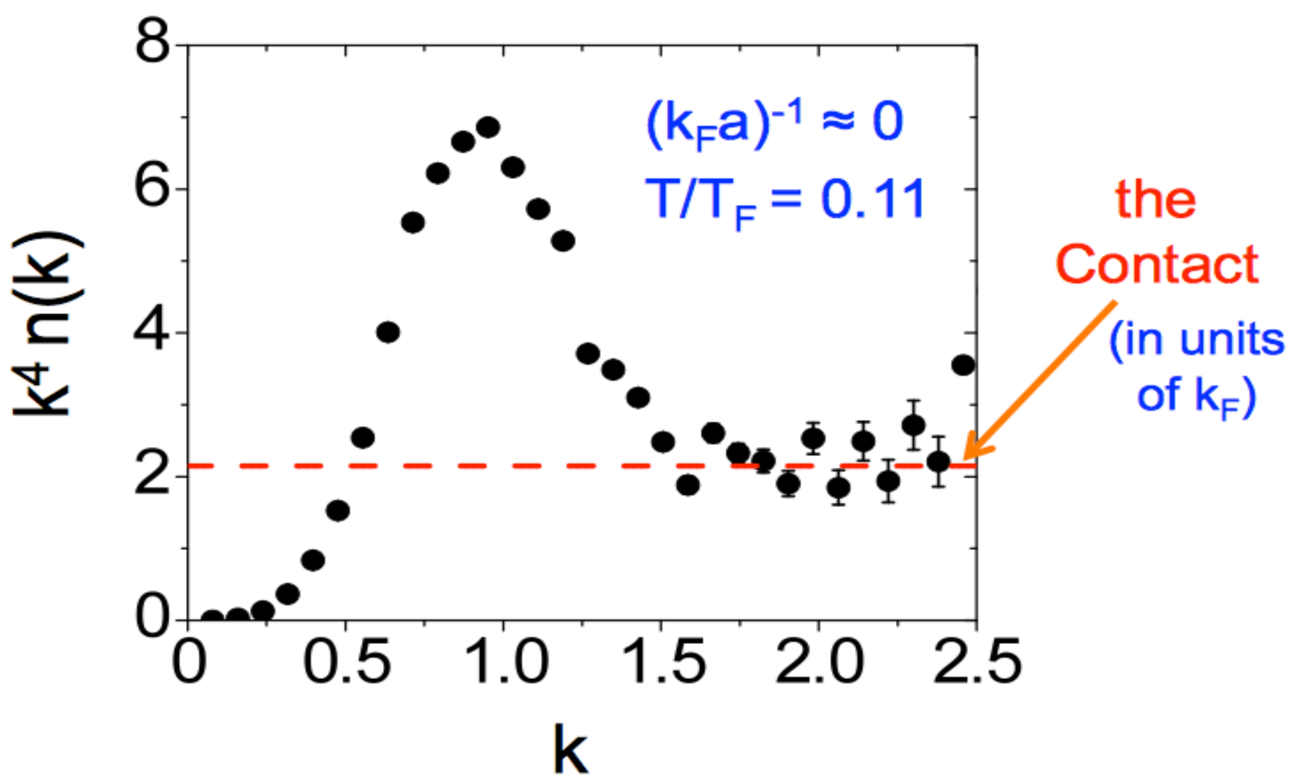
Dilute System → Short Distance Factorization → **High Momentum Tail**

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

Experimental Validation

Two spin-state mixtures of ultra-cold ^{40}K and ^{6}Li atomic gas systems.

=> extracted the contact and verified the universal relations



Stewart et al. PRL **104**, 235301 (2010)

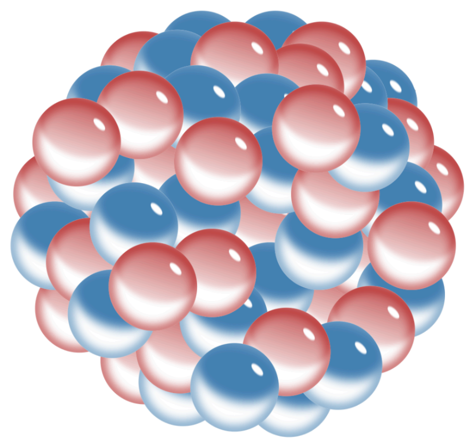
What About
a *Nuclear*
Contact ?

A Nuclear Contact?

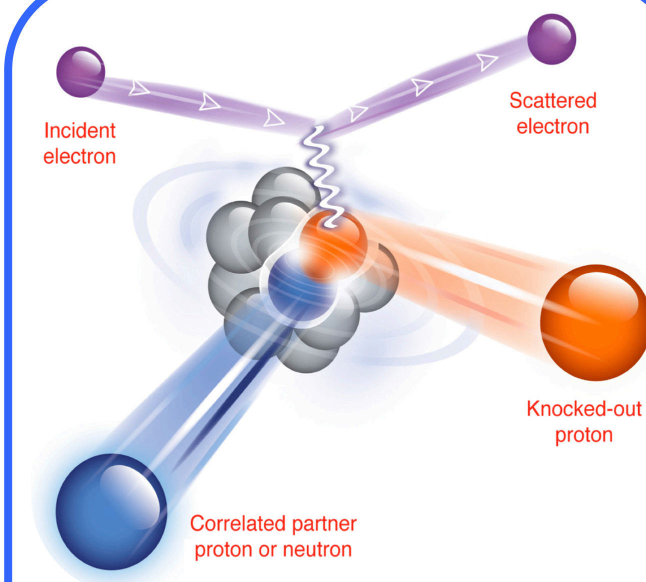
Concept developed for:

dilute two-component Fermi systems with a short-range interaction.

?



protons and neutrons



2N-SRC

Theory Says: not so much

Are nuclei dilute? (i.e. $r_{eff} << a,d$)

$$d = \left(\rho / 2 \right)^{-1/3} \approx 2.3 \text{ fm}$$

$$r_{eff} \approx \frac{\hbar}{2 \cdot m_\pi \cdot c} \approx 0.7 \text{ fm}$$

[Tensor force]

$$a\left({}^3S_1\right) = 5.42 \text{ fm}$$

$$r_{eff}(0.7 \text{ fm}) \ < \ d(2.3 \text{ fm}),\ a(5.4 \text{ fm})$$

But Experiment Says….

Is there $1/k^4$ scaling regardless?

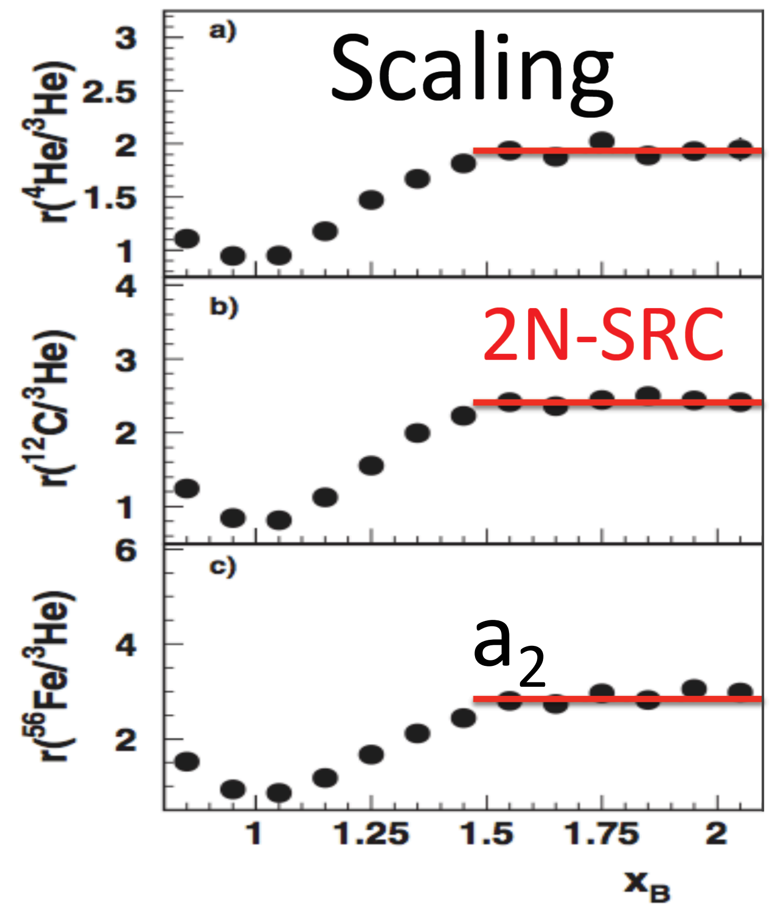
$$1.5k_F < k < 3k_F$$

$$n_A(k) = a_2(A/d)\cdot n_d(k)$$

nucleus A momentum distribution

experimental constant

deuteron momentum distribution



The momentum distribution of nucleons in medium to heavy nuclei is proportional to that of deuteron at high momenta.

But Experiment Says.... **Yes!**

Is there $1/k^4$ scaling regardless?

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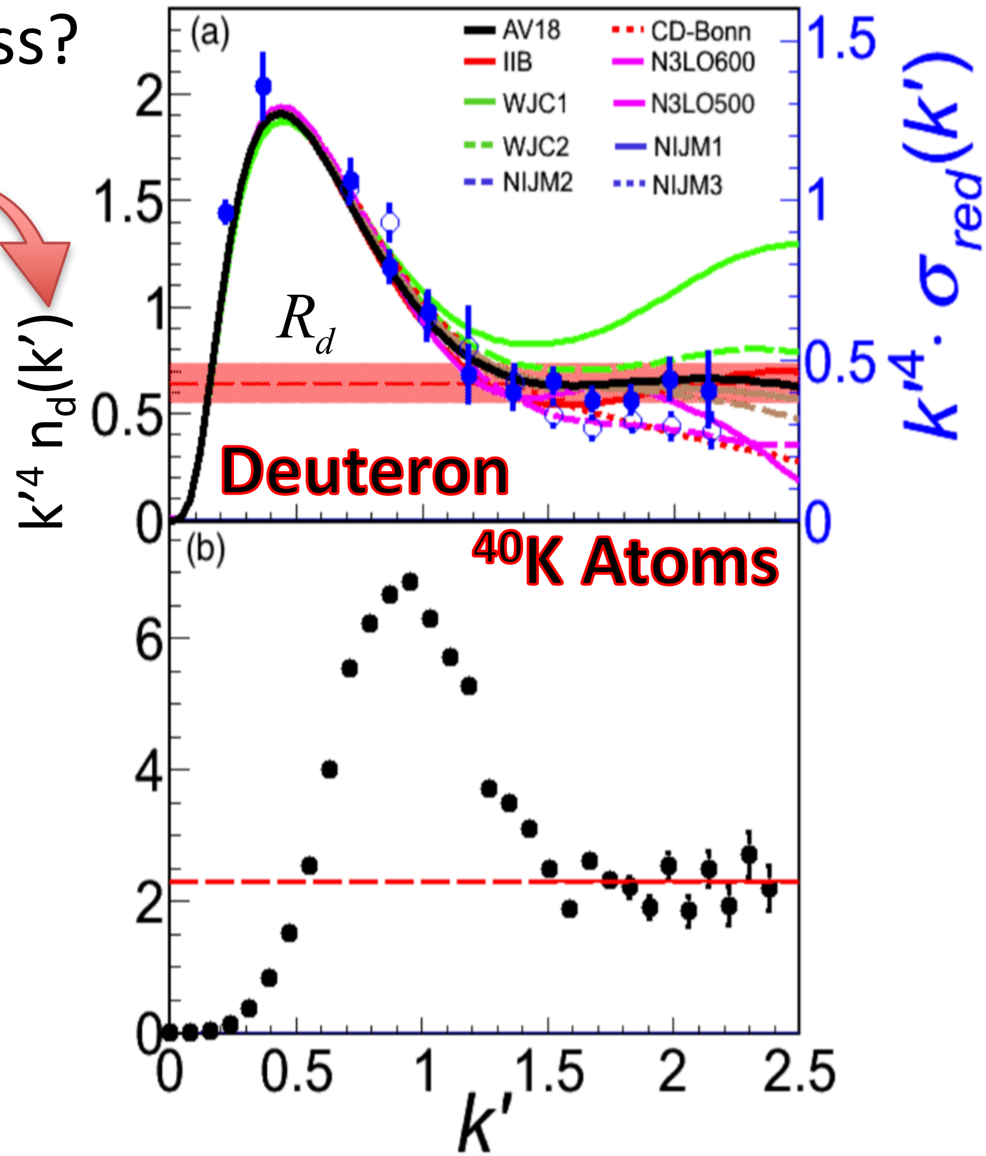


O. Hen et al. Phys. Rev. C **92**, 045205 (2015)

But Experiment Says…. **Yes! (?)**

Is there $1/k^4$ scaling regardless?

$$1.5k_F < k < 3k_F$$

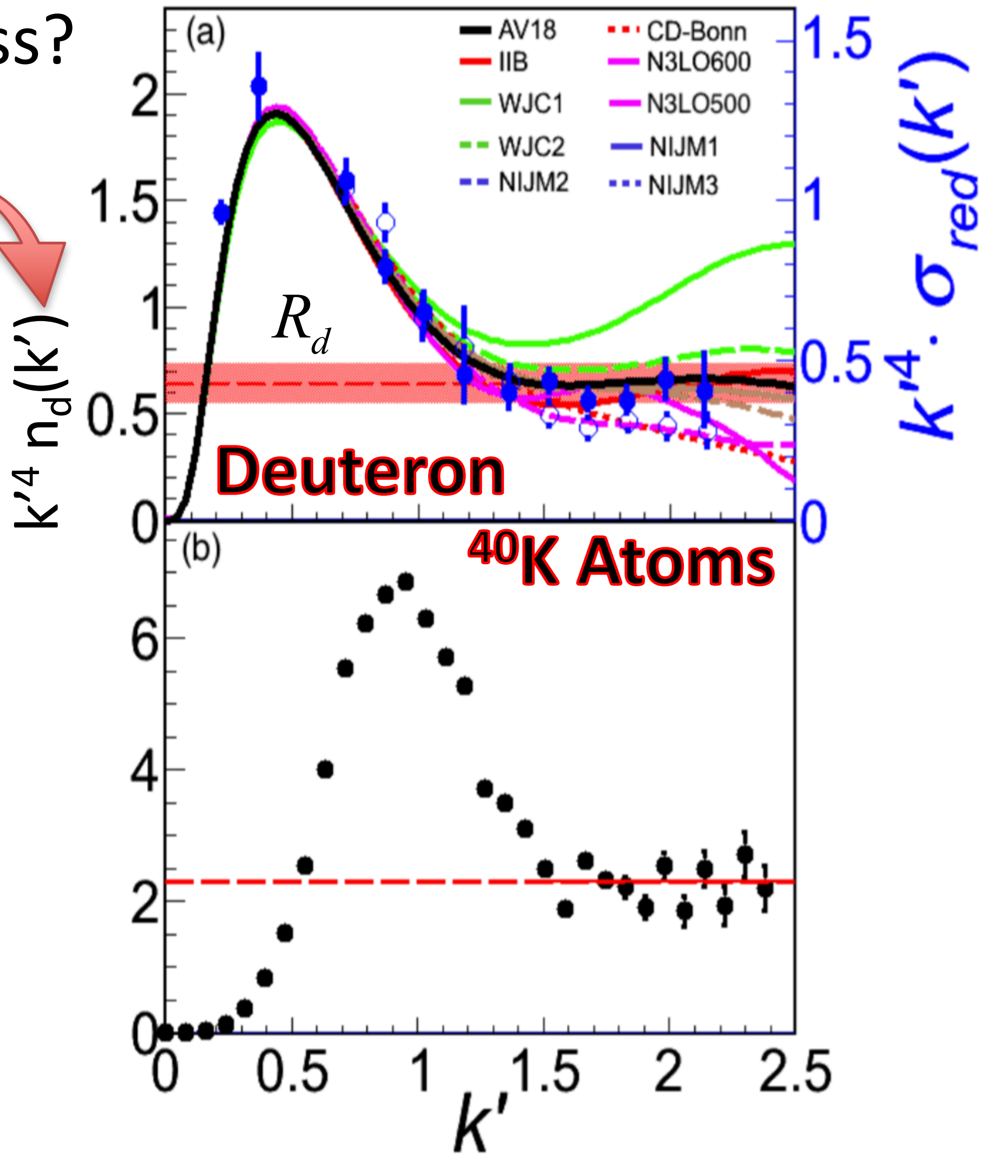
$$n_A(k) = a_2(A/d)\cdot n_d(k)$$

Why $1/k^4$?

Effect of the one pion exchange (OPE) contribution to the tensor potential acting in second order

$$\left(-B-H_0\right)\left|\Psi_D\right\rangle = V_T\left|\Psi_S\right\rangle$$

$$V_{00} = V_T\left(-B-H_0\right)^{-1}V_T$$



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Is there $1/k^4$ scaling regardless?

$$1.5k_F < k < 3k_F$$

$$n_A(k) = a_2(A/d) \cdot n_d(k)$$

$$\frac{C}{k_F \cdot A} = a_2(A) \cdot R_d$$

Nucleus	$a_2(A)$	$\frac{C}{k_F A}$
^{12}C	4.75 ± 0.16	3.04 ± 0.49
^{56}Fe	5.21 ± 0.20	3.33 ± 0.54
^{197}Au	5.16 ± 0.22	3.30 ± 0.53

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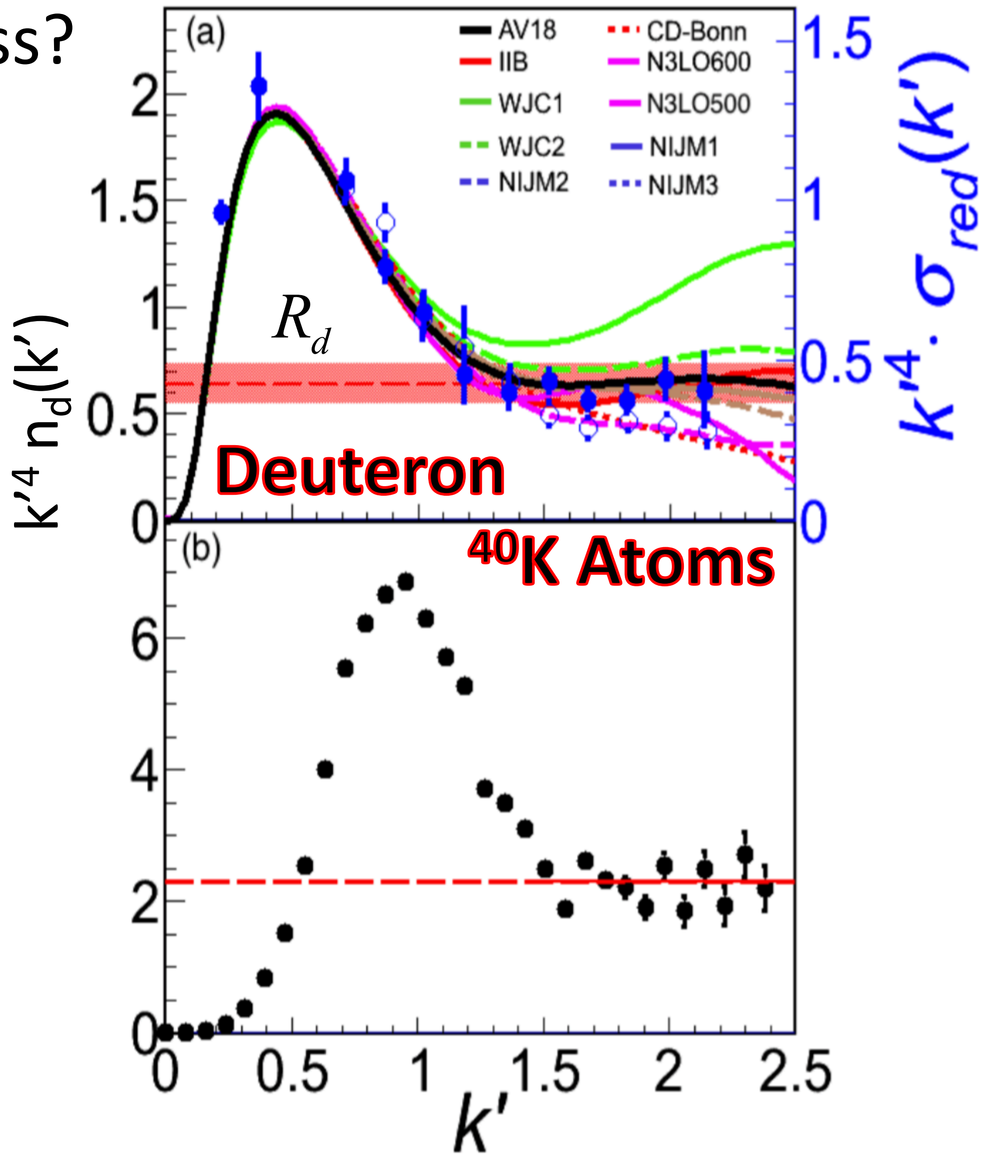
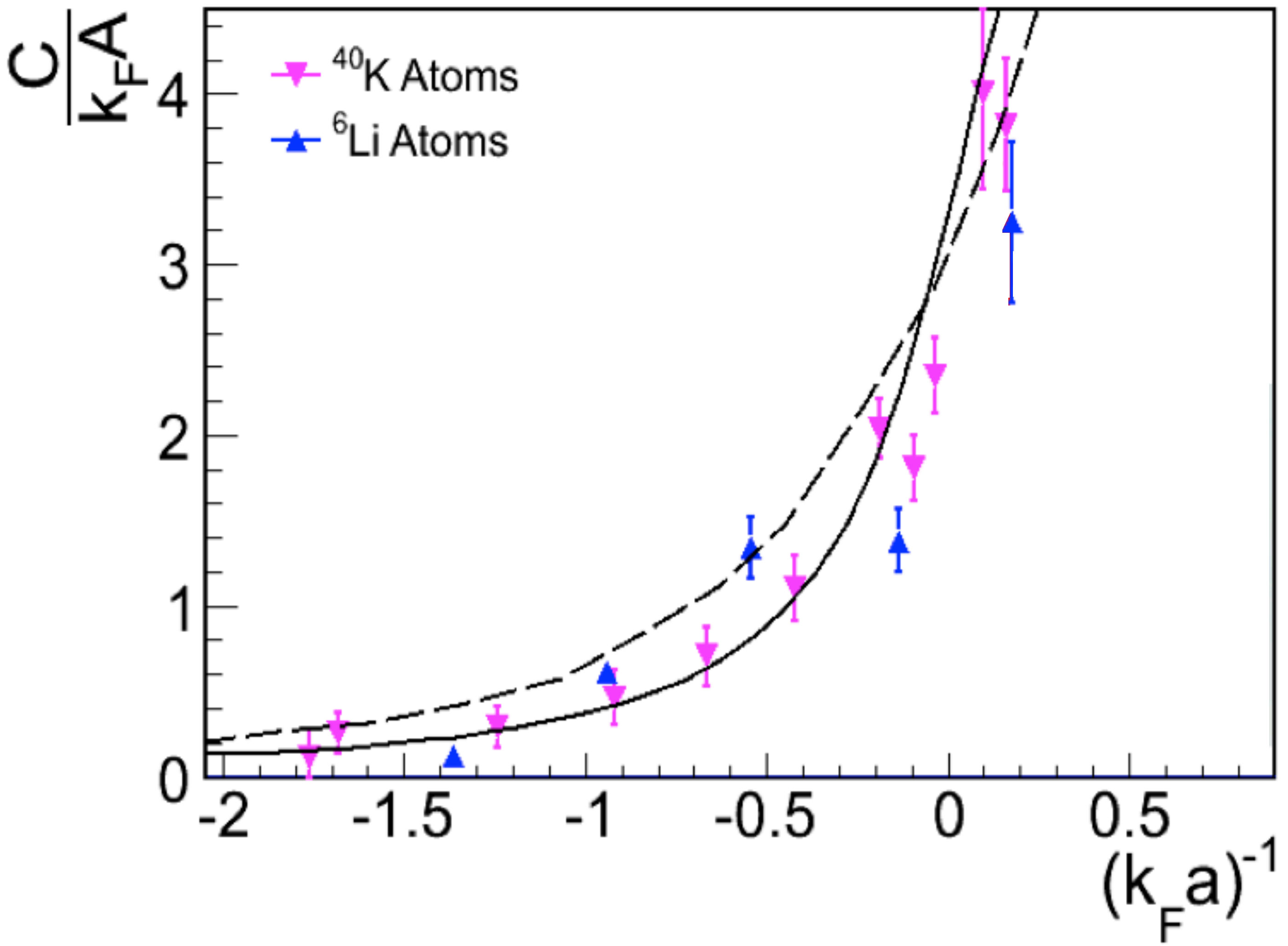


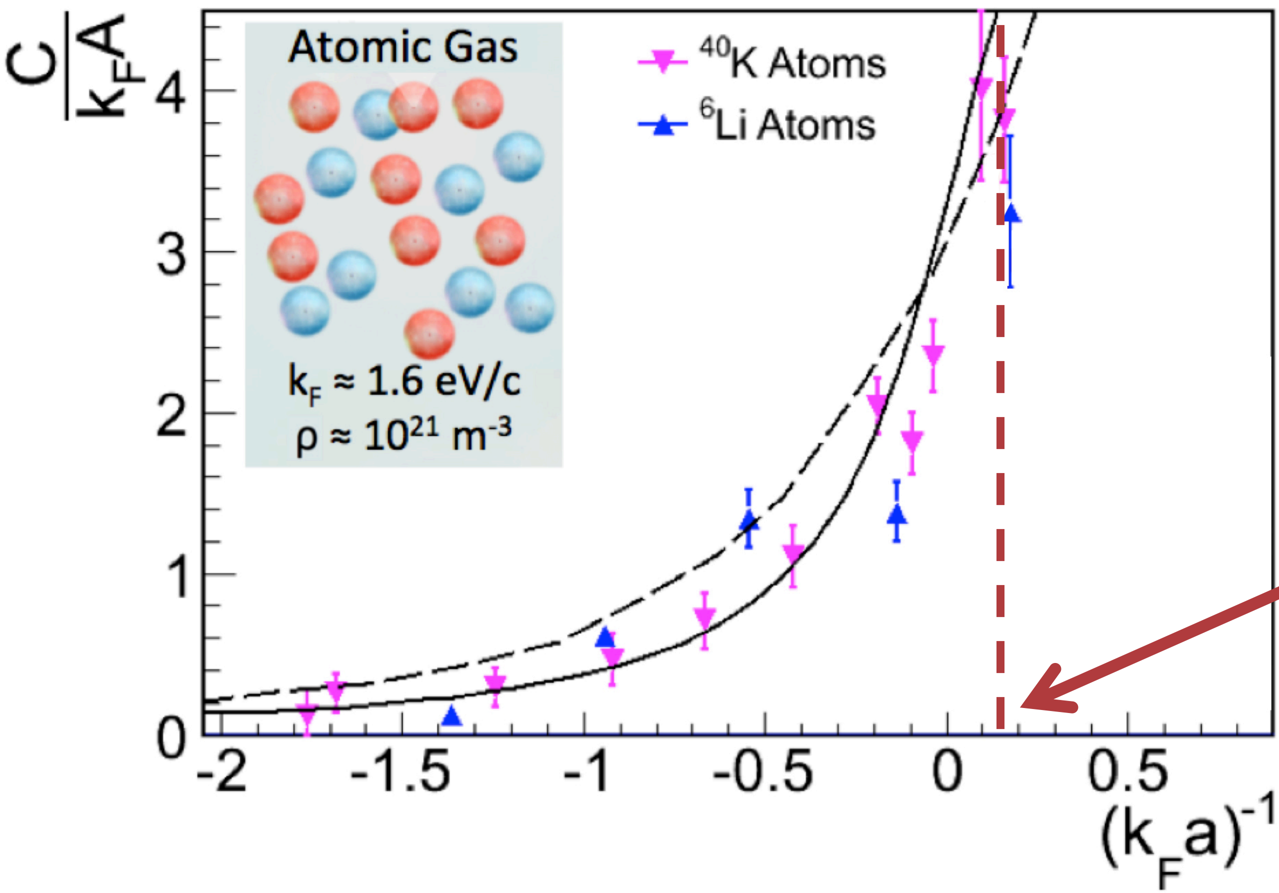
Comparing with atomic systems



Stewart et al. Phys. Rev. Lett. **104**, 235301 (2010)
Kuhnle et al. Phys. Rev. Lett. **105**, 070402 (2010)

Comparing with atomic systems

Finding the same *dimensionless* interaction strength



For Nuclei:

$k_F \approx 1.27$ fm^{-1}

$a \approx 5.4$ fm

$(k_F a)^{-1} \approx 0.15$

Stewart et al. Phys. Rev. Lett. **104**, 235301 (2010)
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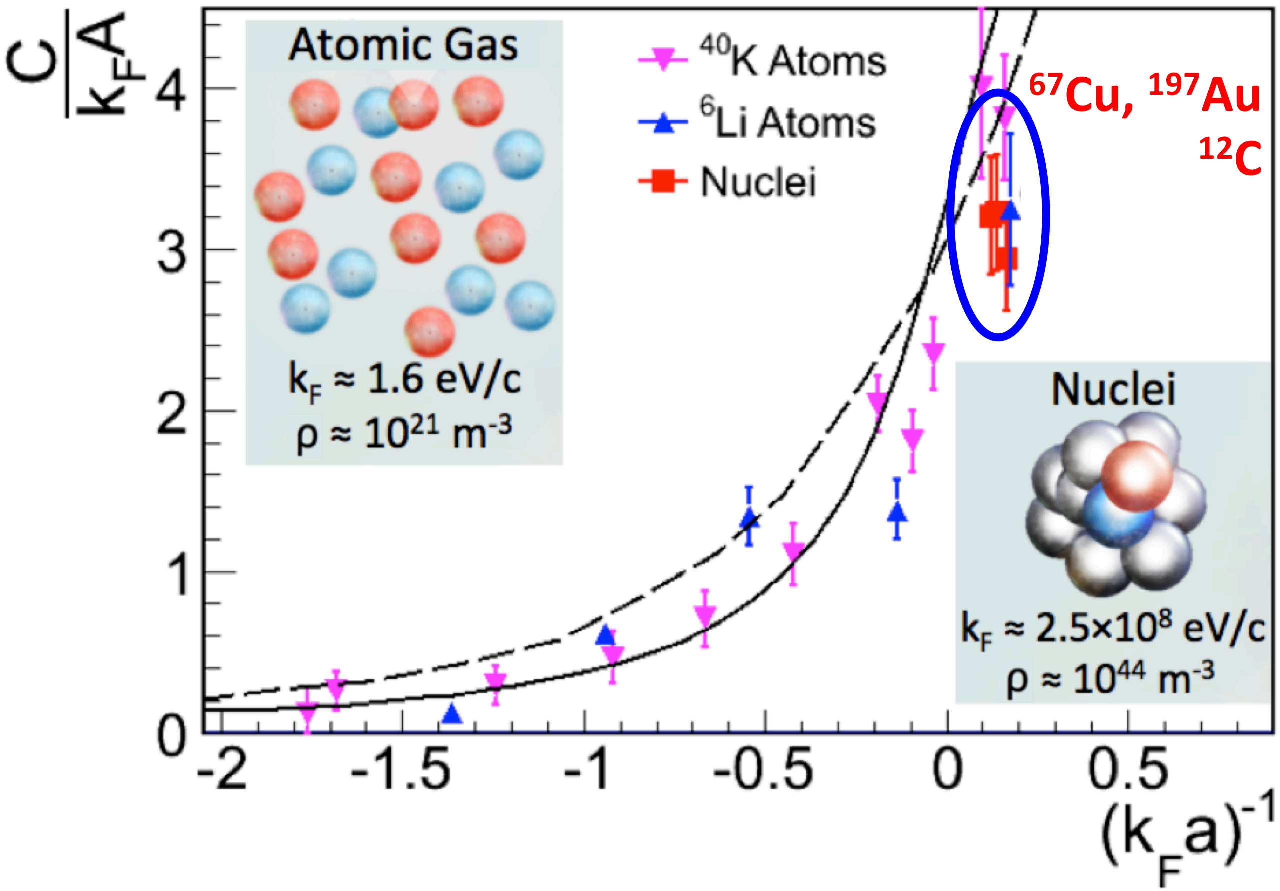
Comparing with atomic systems

Equal contacts for equal interactions strength!



For Nuclei:

$k_F \approx 1.27\ \mathrm{fm}^{-1}$

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$(k_F a)^{-1} \approx 0.15$

Nucleus	$\frac{C}{k_F A}$
^{12}C	3.04 ± 0.49
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$$\frac{C}{k_F \cdot A} = a_2(A) \cdot R_d$$

O. Hen et al. Phys. Rev. C **92**, 045205 (2015)
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How can we reconcile the experimental observation with theory expectation?

i.e. is there a region in which the nuclear wave function fully factorizes?

Going Back to the Theory…

1. Generalize the contact formalism to nuclear systems.
2. Use it to make specific predictions of nuclear properties.
3. Check using experimental data and full many-body calculations.

The Contact and Universal Relations

Issue: Scale separation does not necessarily work in nuclear systems.

Solution: assume a more general form for the 2-body wavefunction.

Atomic System:

$$\boxed{\Psi \xrightarrow[r_{ij}\to 0]{} (1/r_{ij} - 1/a) A_{ij}(\mathbf{R}_{ij}, \{\mathbf{r}_k\}_{k\neq i,j})}$$

Nuclear System:

$$\boxed{\Psi \xrightarrow[r_{ij}\to 0]{} (\ \boldsymbol{\varphi}(r)_{ij}\ ) A_{ij}(\mathbf{R}_{ij}, \{\mathbf{r}_k\}_{k\neq i,j})}$$

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Nuclear System:

$$\Psi \xrightarrow[r_{ij}\to 0]{} (\ \boldsymbol{\varphi(r)_{ij}}\ ) A_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})$$

known solution for the two-body (nuclear) problem

Factorization in Nuclei

Consider the factorized wave function:

$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_{\alpha} \varphi_{\alpha}(\boldsymbol{r}_{ij}) A^{\alpha}_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})$$

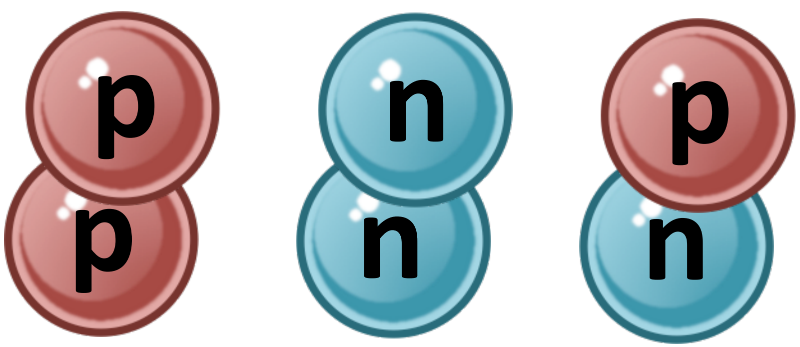
In nuclear physics we have 3 possible types of pairs:

ij = {pp, nn, pn}

+

For each pair we have different channels

α = (s,l)jm



$\downarrow \uparrow$

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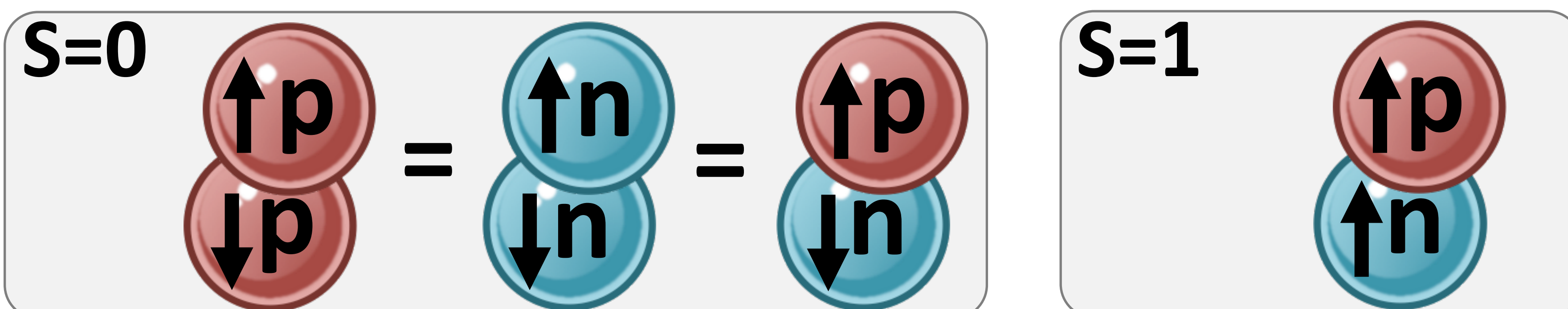
Reduced to 2 contacts by imposing L=0 and symmetry considerations



Relating to Momentum Space

$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_{\alpha} \varphi_{\alpha}(\boldsymbol{r}_{ij}) A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})$$

One Body:

$$\boldsymbol{n_p(k)} = \sum_{\alpha} \left|\tilde{\varphi}_{pp}^{\alpha}(\boldsymbol{k})\right|^2 2C_{pp}^{\alpha} + \sum_{\alpha} \left|\tilde{\varphi}_{pn}^{\alpha}(\boldsymbol{k})\right|^2 C_{pn}^{\alpha}$$

2-Body momentum distributions

- One Body momentum distribution [$n_N(k)$]: Probability to find a nucleon, N, in the nucleus with momentum k.

- Two Body momentum distribution [$n_{NN}(q,Q)$]: Probability to find a NN pair in the nucleus with relative (c.m.) momentum q (Q).

$n_{NN}(q,Q)$ – computational Frontier!

Momentum Space Factorization

$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_{\alpha} \varphi_{\alpha}(r_{ij}) A_{ij}^{\alpha}(R_{ij}, \{r_k\}_{k\neq i,j})$$

One Body:

$$n_p(k) = \sum_{\alpha} \left|\tilde{\varphi}_{pp}^{\alpha}(k)\right|^2 2C_{pp}^{\alpha} + \sum_{\alpha} \left|\tilde{\varphi}_{pn}^{\alpha}(k)\right|^2 C_{pn}^{\alpha}$$

Two body:

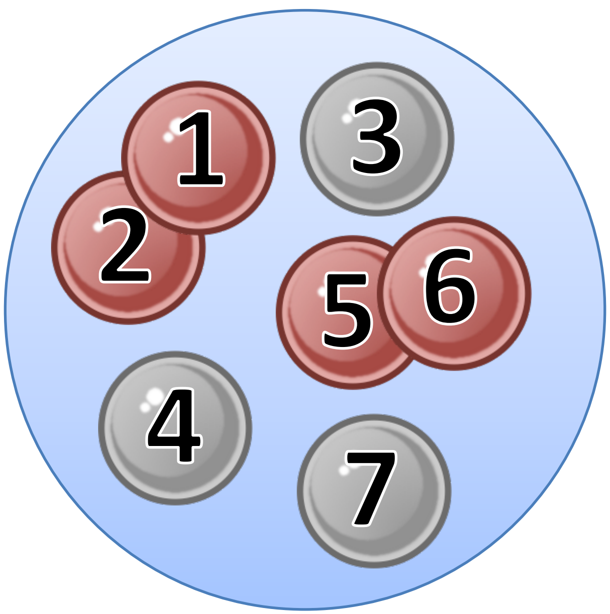
$$F_{ij}(k) = \sum_{\alpha} \left|\tilde{\varphi}_{ij}^{\alpha}(k)\right|^2 C_{ij}^{\alpha}$$

Clearly:

$$n_p(k) \xrightarrow[k\to\infty]{} 2F_{pp}(k) + F_{pn}(k)$$

Two-Body Momentum Distributions

- $n_{NN}(q,Q)$ – Mathematical object that counts all possible NN pairs, regardless of their state:

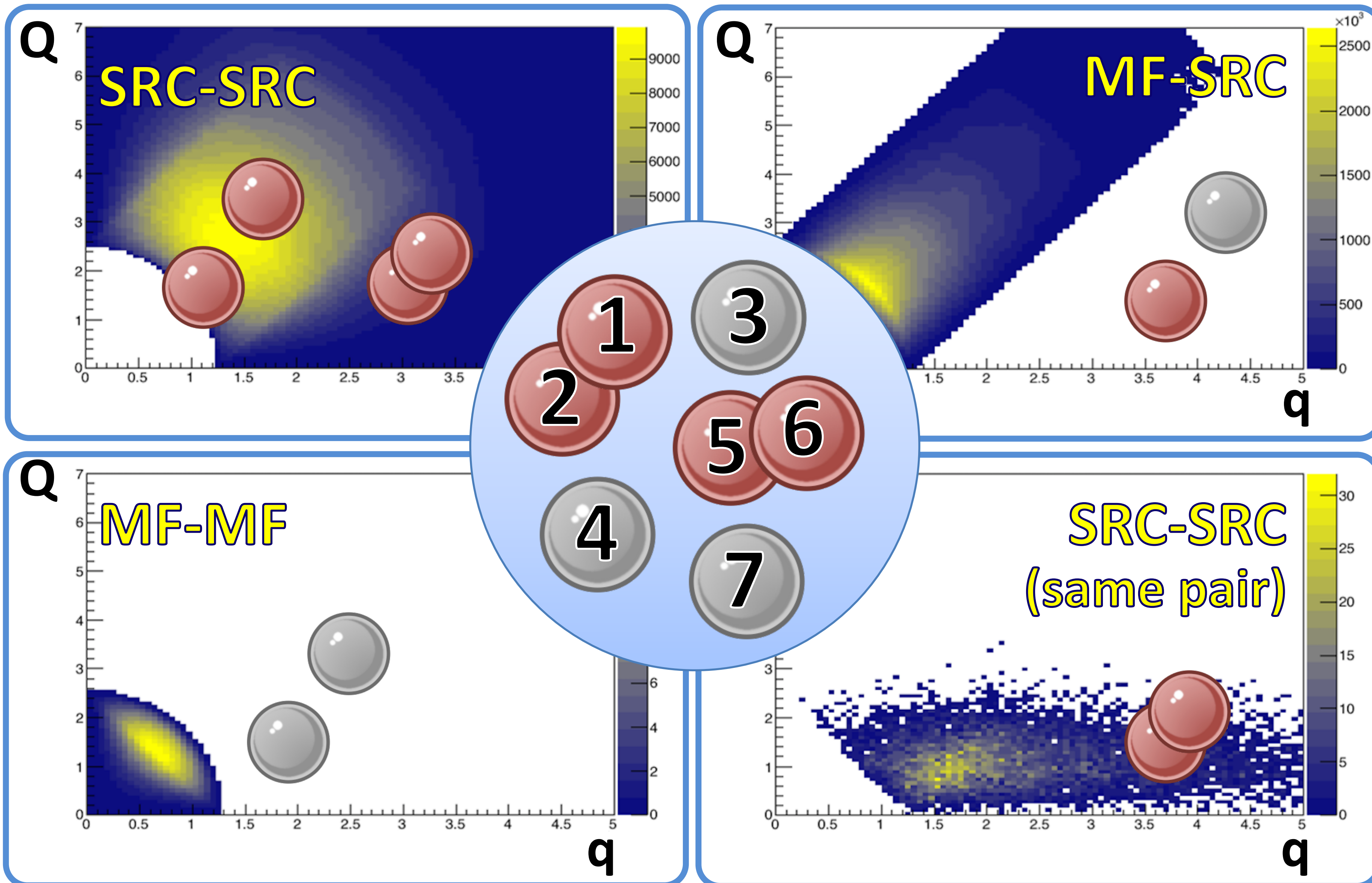


Consider all NN pairs:

1-2	2-3	3-4	4-5	**5-6**	6-7
1-3	2-4	3-5	4-6	5-7	
1-4	**2-5**	3-6	4-7		
1-5	**2-6**	3-7			
1-6	2-7				
1-7					

$n_{NN}(q,Q)$

Toy model to the rescue



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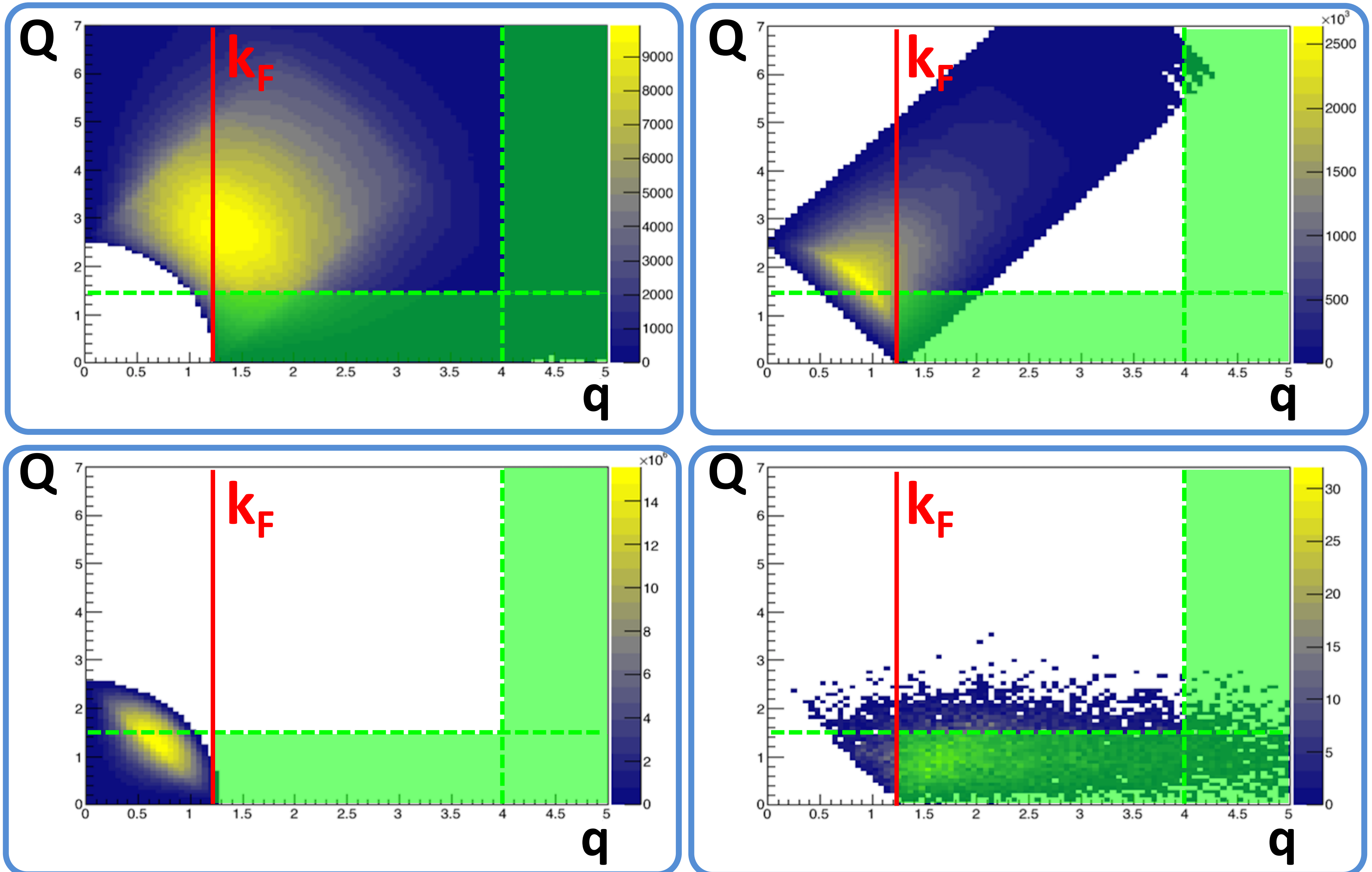
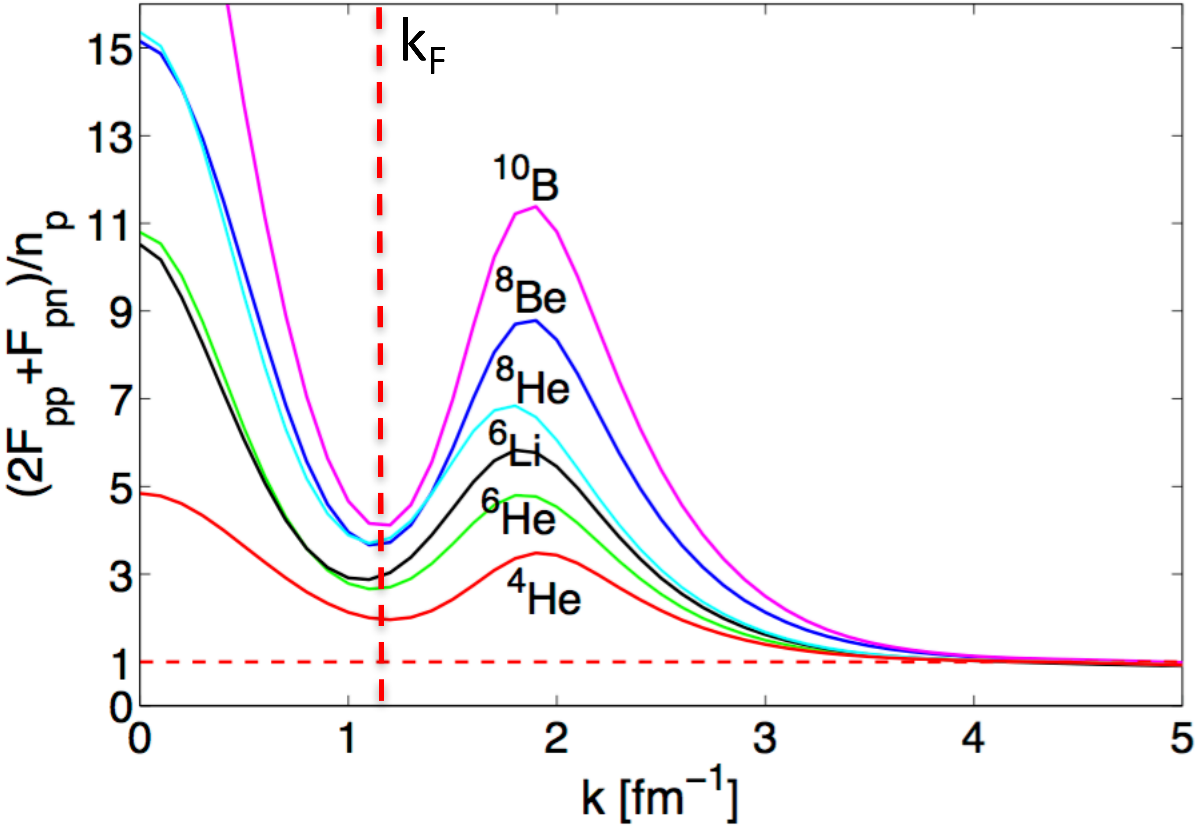


Two-Body Scaling for **High q**

- Weiss and Barnea (PRC 2015): contact interactions dominate when $n_{pn}(q)+2n_{pp}(q) = n_p(k)$



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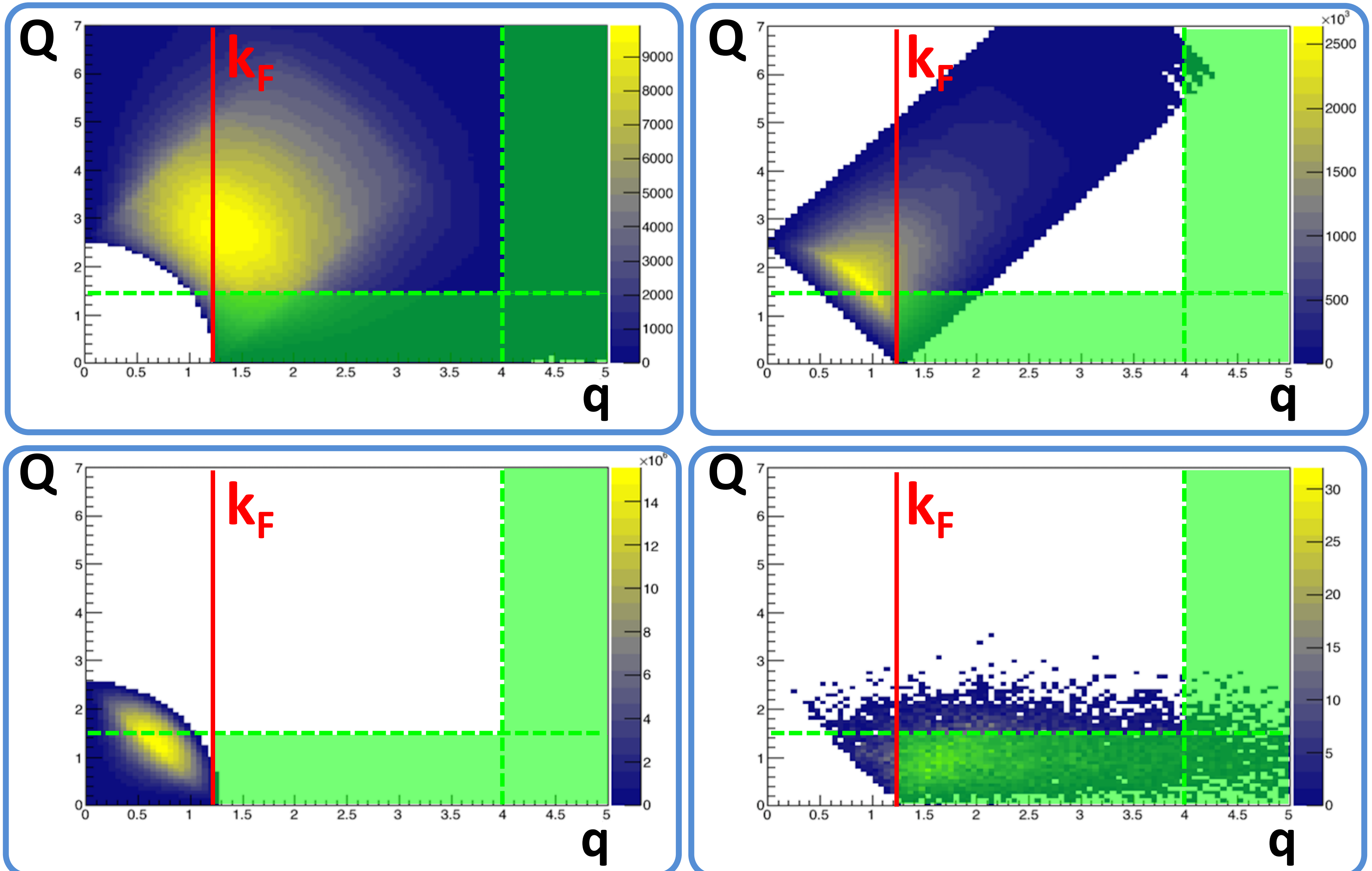
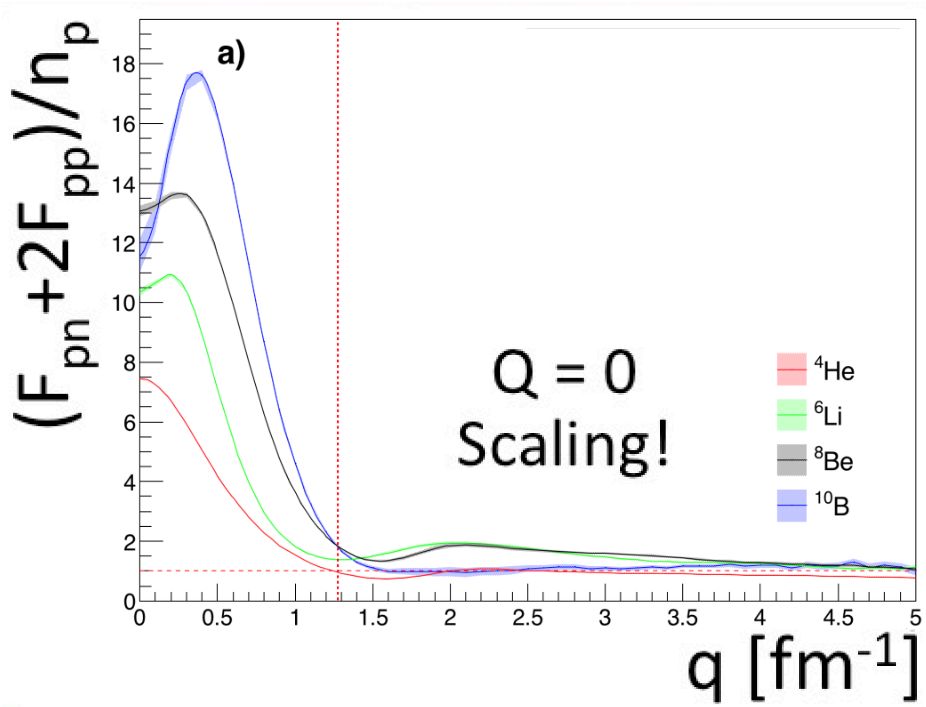
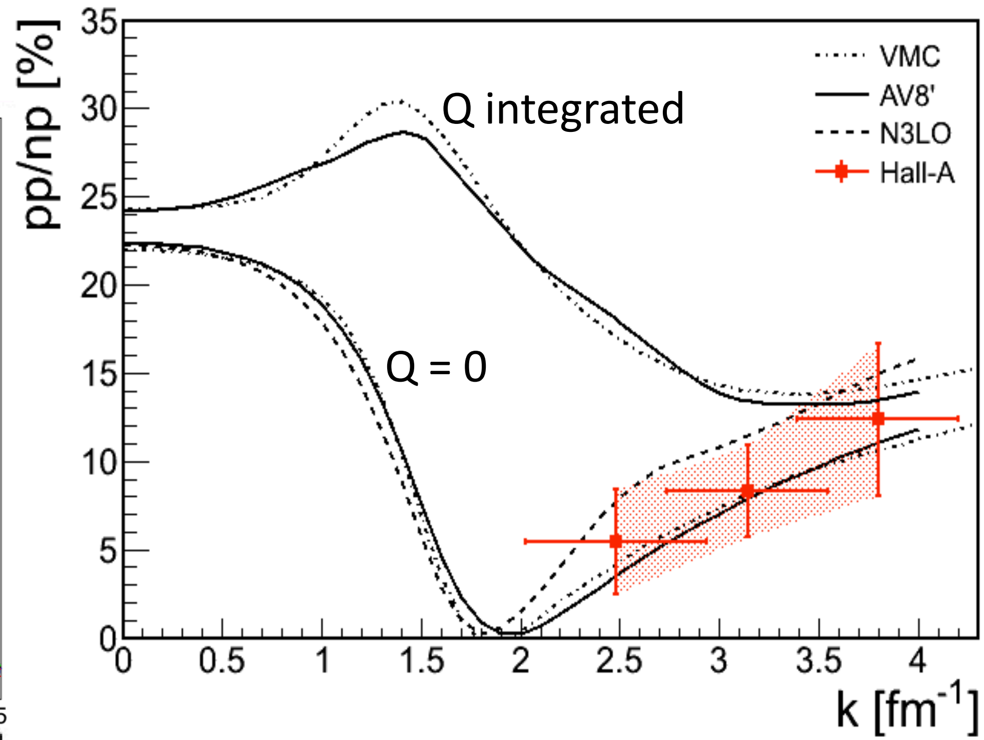


Two-Body Scaling for **Q=0**

- Restricting Q=0 restores scaling starting from $k>k_F$ AND gives consistent results with experimental data!



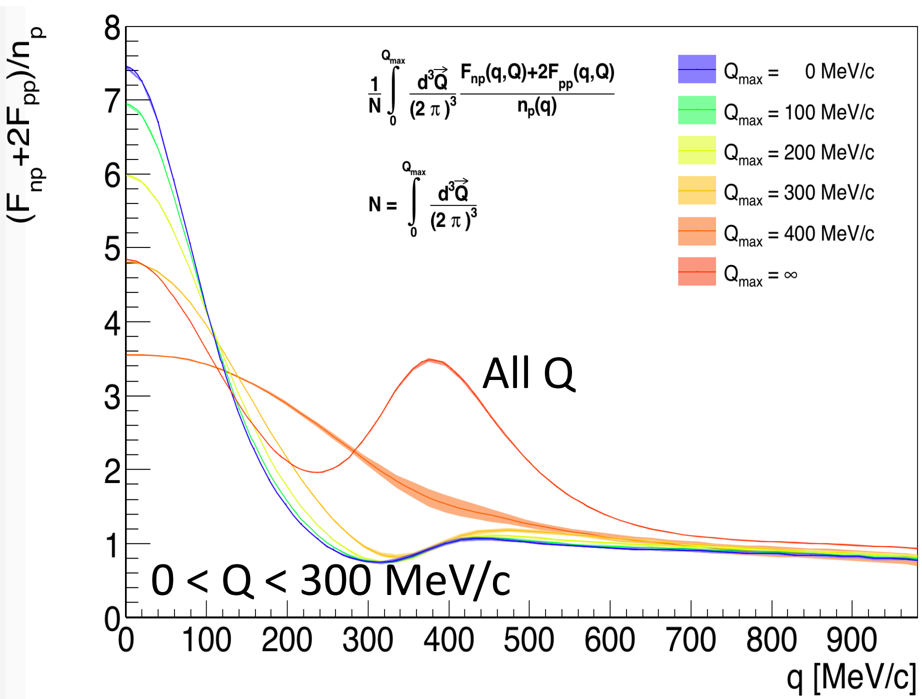


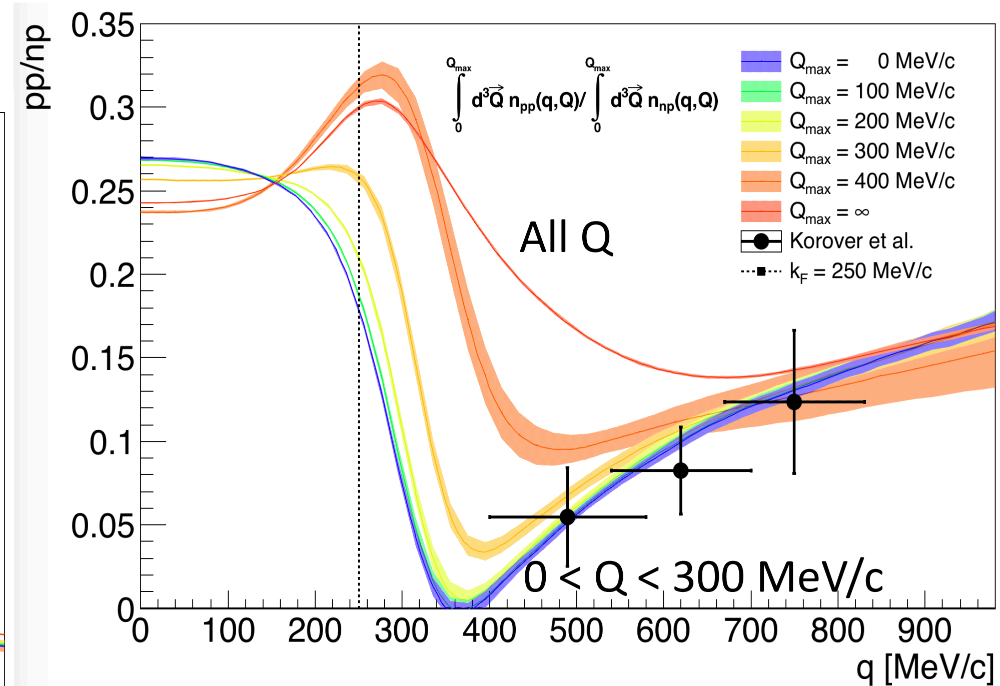
SRC pairs are consistent with Q = 0 *back-to-back* pairs

R. Wiringa et al., Phys. Rev. C 89, 024305 (2014).
T. Neff, H. Feldmeier and W. Horiuchi, Phys. Rev. C 92, 024003 (2015).
I. Korover, N. Muangma, and O. Hen et al., Phys. Rev. Lett 113, 022501 (2014).
Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, arXiv 1612.00923 (2016)

Two-Body Scaling for **Low Q**

- Restricting Q=0 restores scaling starting from $k>k_F$ AND gives consistent results with experimental data!





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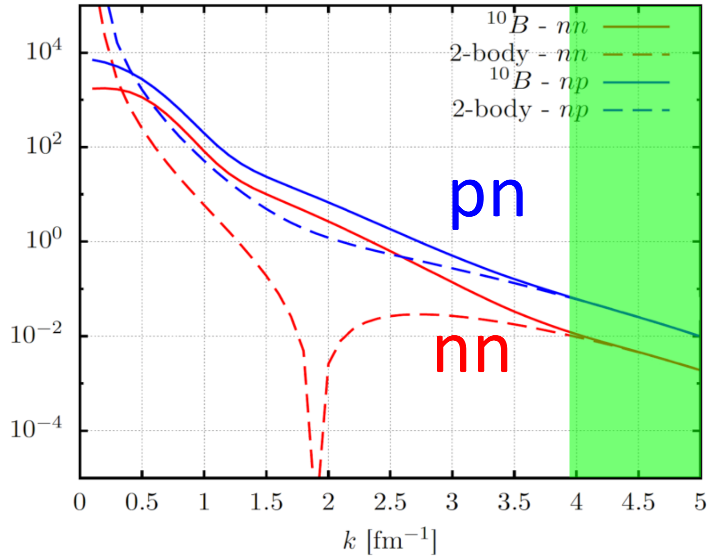
Extracting the nuclear contact(s)

Extracting the Contacts

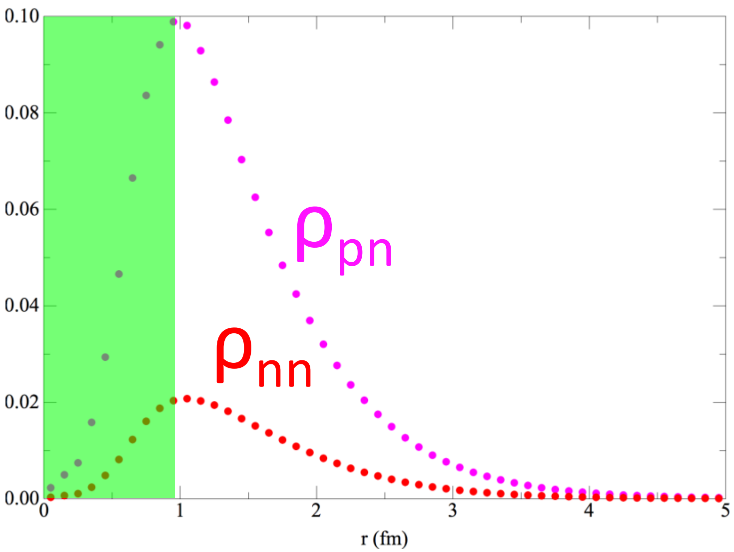


2-Body momentum distributions

$$F_{pn}(k) \xrightarrow[k\to\infty]{} |\varphi^0_{pn}(k)|^2 C^0_{pn} + |\varphi^d_{pn}(k)|^2 C^d_{pn}$$

$$F_{nn}(k) \xrightarrow[k\to\infty]{} |\varphi^0_{nn}(k)|^2 C^0_{nn}$$

Fitting range ~ 4-5 fm^{-1}



2-Body density distributions

$$\rho_{pn}(r) \xrightarrow[r\to 0]{} |\varphi^0_{pn}(r)|^2 C^0_{pn} + |\varphi^d_{pn}(r)|^2 C^d_{pn}$$

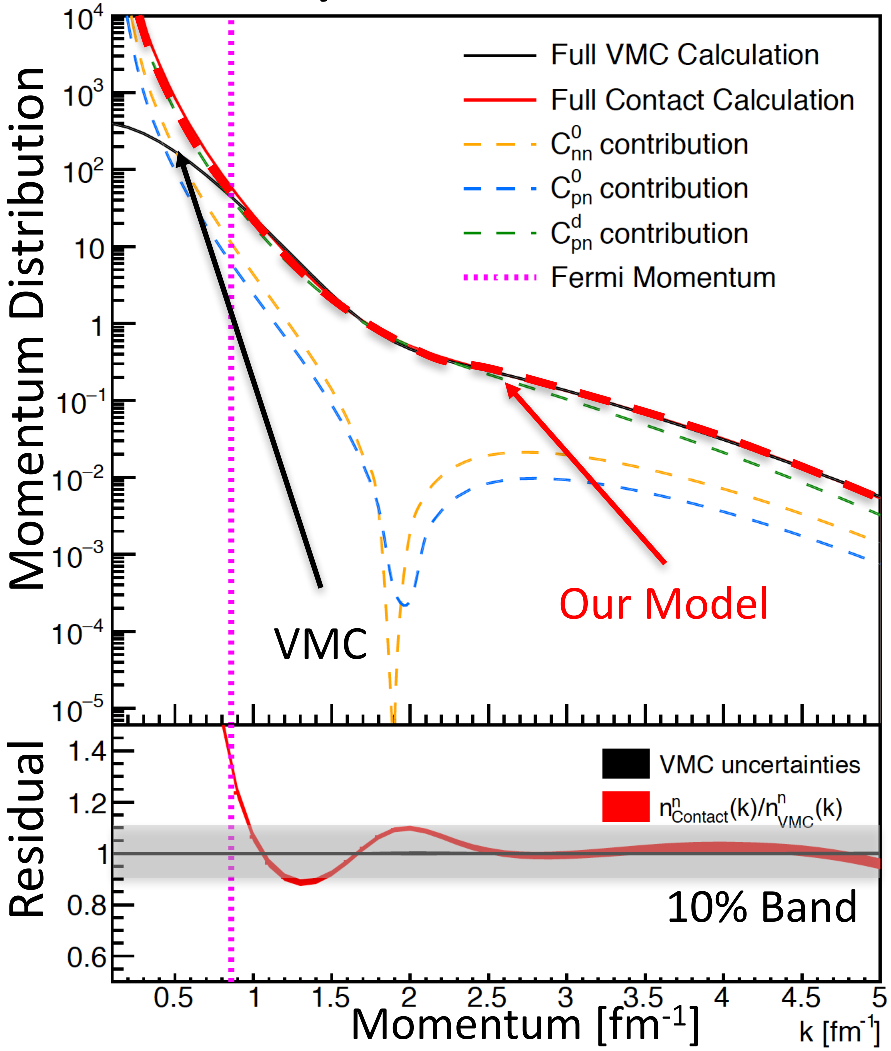
$$\rho_{nn}(r) \xrightarrow[r\to 0]{} |\varphi^0_{nn}(r)|^2 C^0_{nn}$$

Fitting range ~ 0.25-1 fm

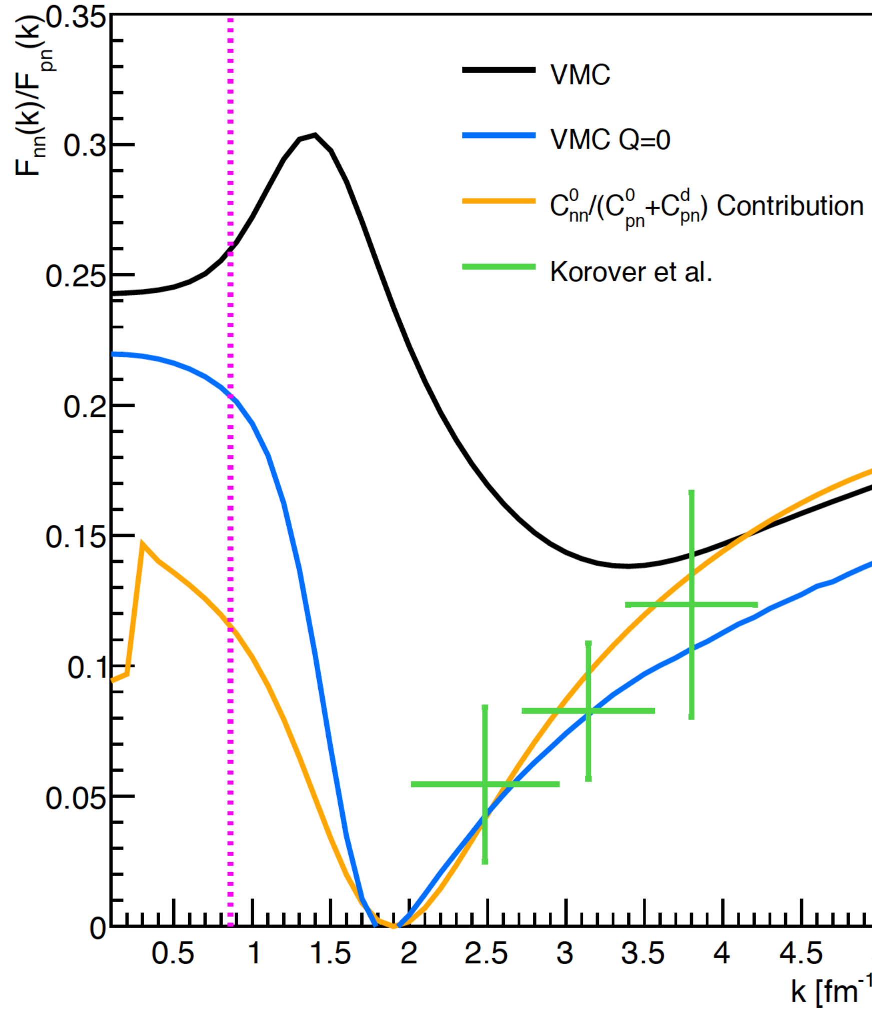
R. B. Wiringa *et al.*, PRC 89, no. 2, 024305 (2014).
Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, arXiv 1612.00923 (2016)

^{4}He Results

1-body Momentum dist.



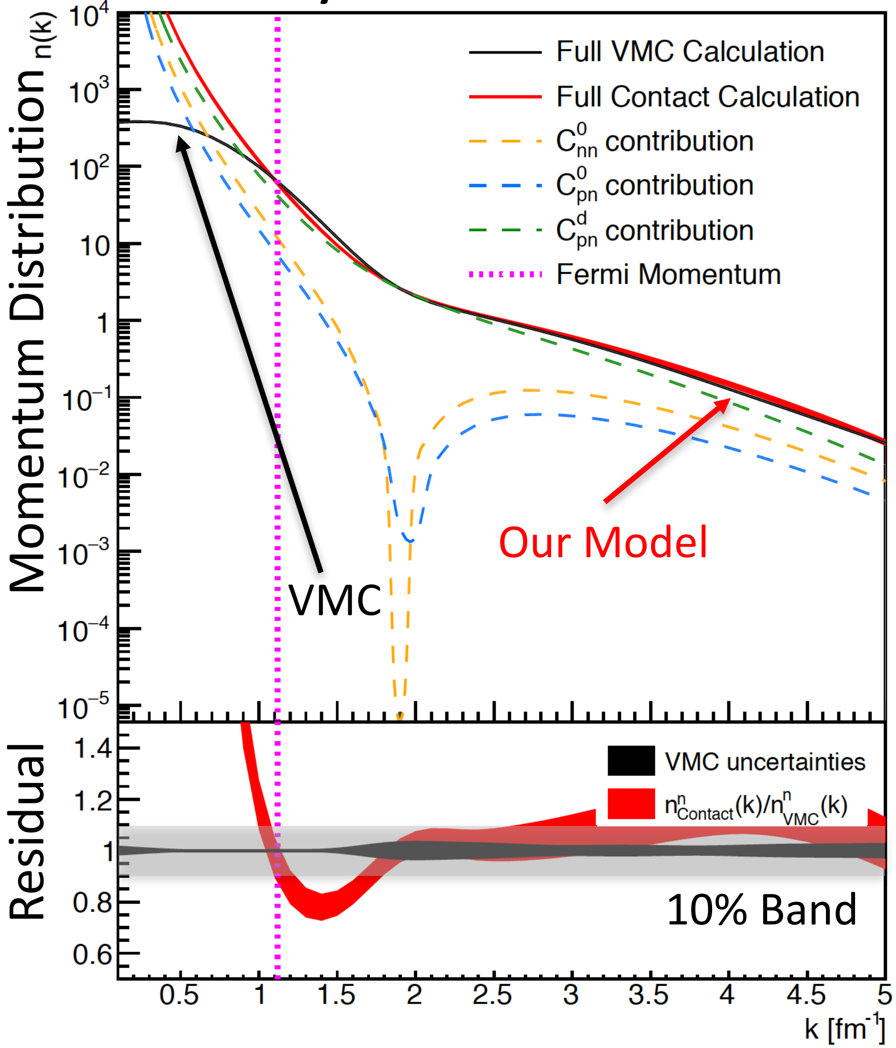
pp / np ratio



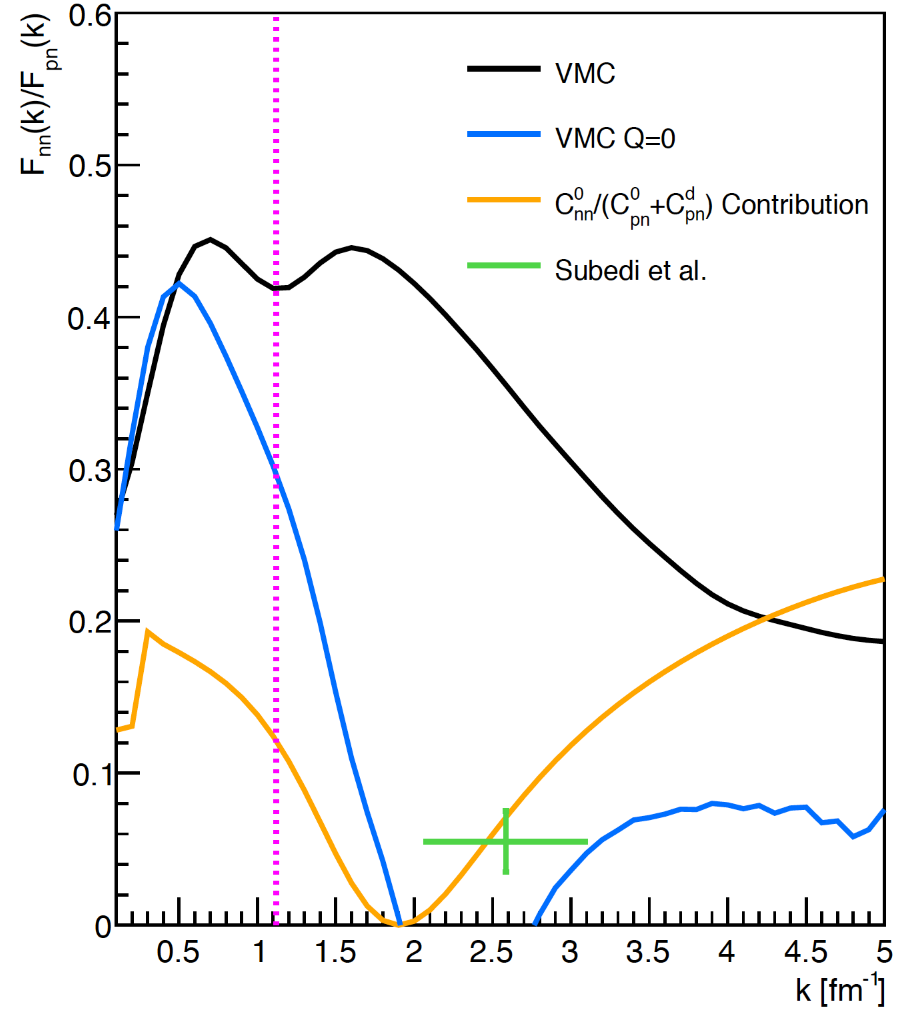
Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, arXiv 1612.00923 (2016)

^{12}C Results

1-body Momentum dist.

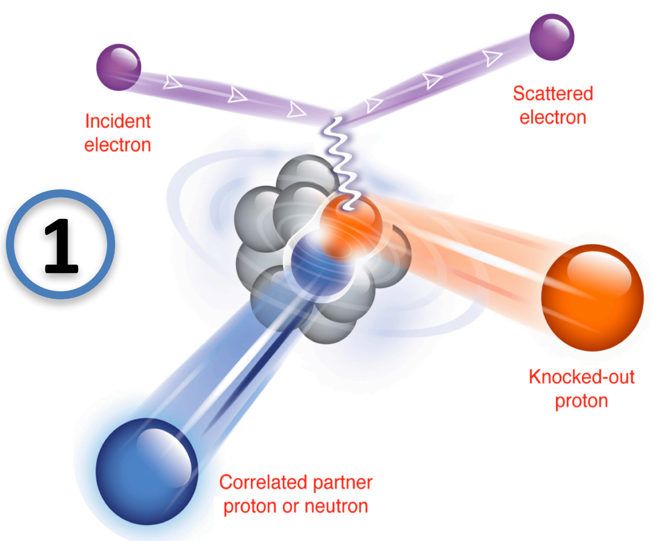


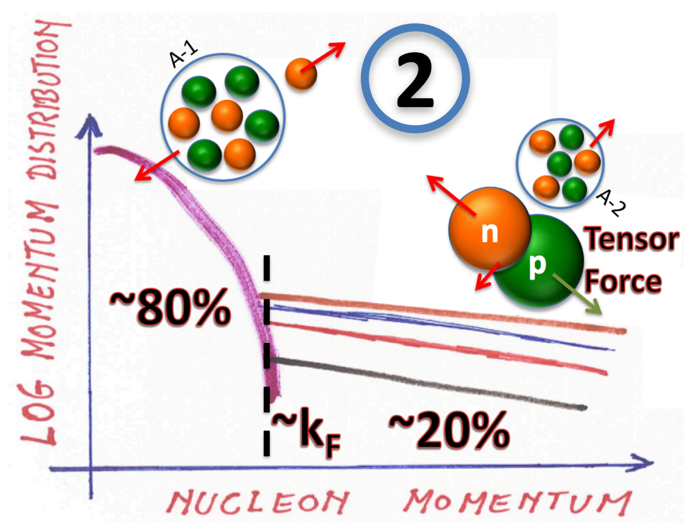
pp / np ratio

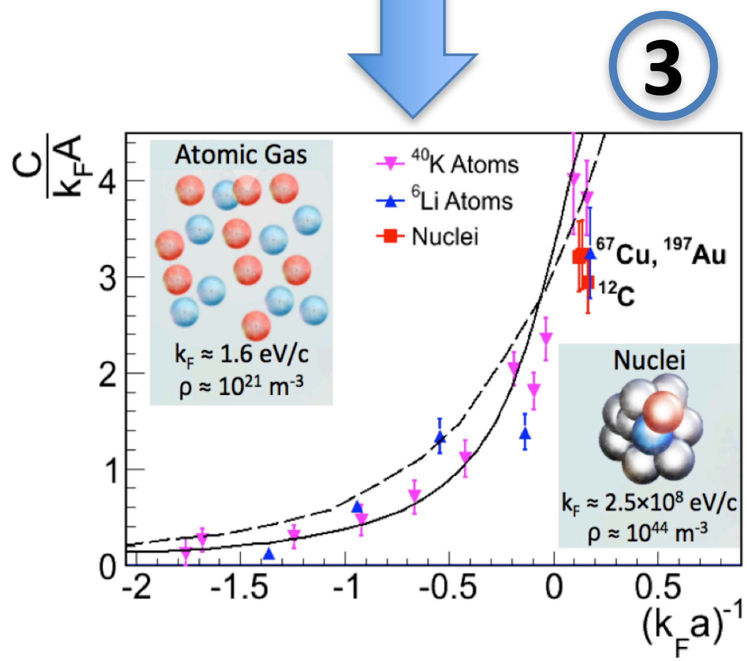


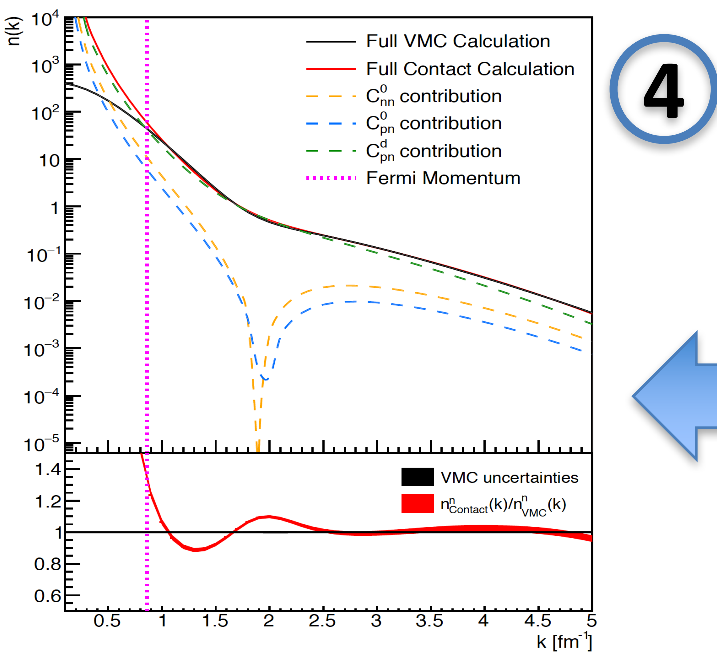
Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, arXiv 1612.00923 (2016)

Summery: Exp. to Pheno. to Theory

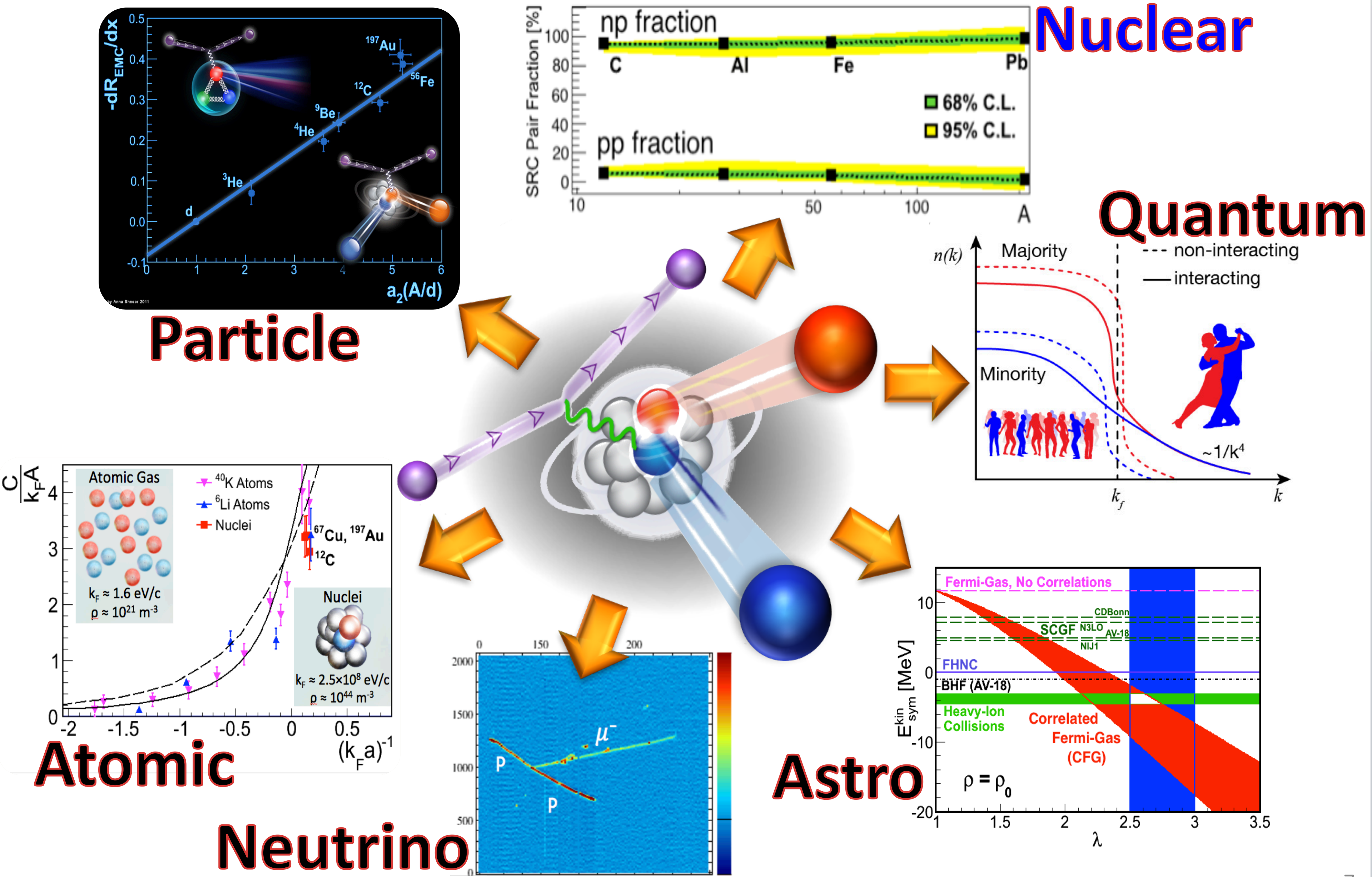






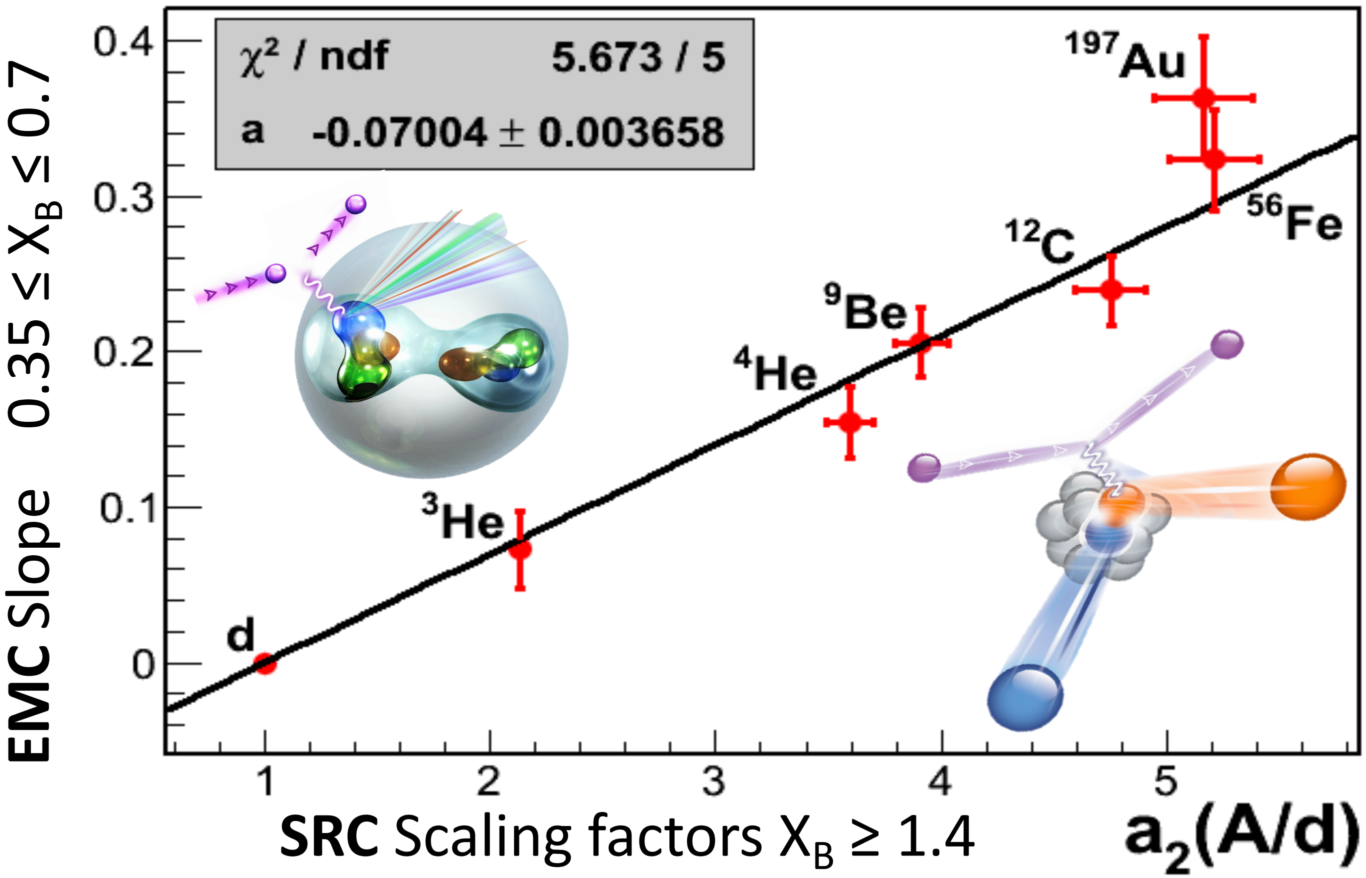


Why SRC?



Nuclear
np fraction
pp fraction
C
Al
Fe
Pb
68% C.L.
95% C.L.
SRC Pair Fraction [%]
A
Particle
-dR_EMC/dx
a_2(A/d)
d
3He
4He
9Be
12C
56Fe
197Au
Quantum
Majority
Minority
non-interacting
interacting
n(k)
~1/k^4
k_f
k
Atomic
Atomic Gas
40K Atoms
6Li Atoms
Nuclei
67Cu, 197Au
12C
k_F ≈ 1.6 eV/c
ρ ≈ 10^21 m^-3
k_F ≈ 2.5×10^8 eV/c
ρ ≈ 10^44 m^-3
C/(k_F A)
(k_F a)^-1
Neutrino
μ-
P
P
Astro
Fermi-Gas, No Correlations
CDBonn
SCGF
N3LO
AV-18
NIJ1
FHNC
BHF (AV-18)
Heavy-Ion Collisions
Correlated Fermi-Gas (CFG)
ρ = ρ_0
E^kin_sym [MeV]
λ

EMC-SRC Correlation



See G. Miller talk yesterday

O. Hen et al., Int. J. Mod. Phys. E. **22**, 1330017 (2013).

O. Hen et al., Phys. Rev. C **85** (2012) 047301.

L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, R. Shneor, Phys. Rev. Lett. **106** (2011) 052301.

Forthcoming RMP Review

Nucleon-Nucleon Correlations and the Quarks Within

Or Hen

Massachusetts Institute of Technology, Cambridge, MA 02139

Gerald A. Miller

Department of Physics, University of Washington, Seattle, WA 98195

Eli Piasetzky

School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

Lawrence B. Weinstein

Department of Physics, Old Dominion University, Norfolk, VA 23529

(Dated: November 2, 2016)

- conventional (non-quark) nuclear physics cannot account for the EMC effect
- models need to include nucleon modification to account for the EMC effect. These models can modify the structure of either:
  - mean field nucleons, or
  - nucleons belonging to SRC pairs.
- there is a phenomenological connection between the strength of the EMC effect and the probability that a nucleon belongs to a two-nucleon SRC pair ($a_2(A)$), see Fig. 33.
- the influence of SRC pairs can account for the EMC-SRC correlation because both effects are driven by high virtuality nucleons with $p^2 \neq M^2$,
- the connection between the EMC effect and the coefficients $a_2(A)$ has been derived using two completely different theories, so that this connection is no accident
- nuclei must contain a small percentage of baryons that are not nucleons. Such baryons exist in the short-ranged correlations and are the source of the EMC effect.

arXiv: 1611.09748 (2016)

Short Range Correlations and the EMC Effect in Effective Field Theory

Jiunn-Wei Chen,[1,2,*] William Detmold,[2,†] Joel E. Lynn,[3,4,‡] and Achim Schwenk[3,4,5,§]

[1] *Department of Physics, CTS and LeCosPA, National Taiwan University, Taipei 10617, Taiwan*
[2] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[3] *Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[4] *ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[5] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

arXiv: 1607.03065 (2016)

Gerald A. Miller

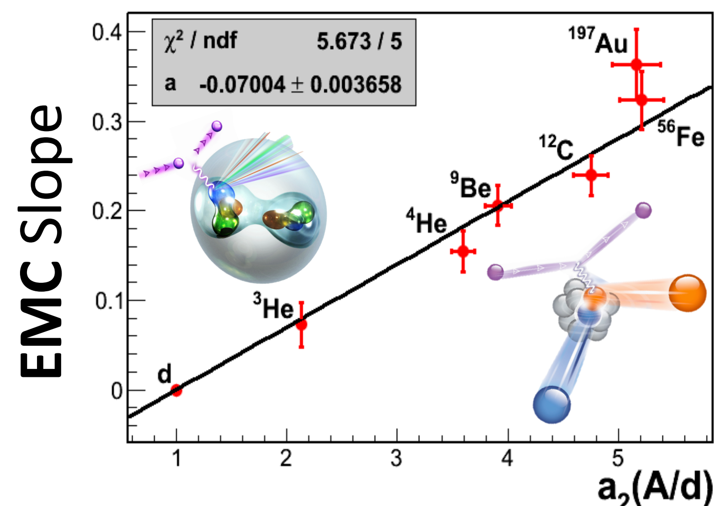
EFT description of bound nucleon structure:

$$F_2^A(x,Q^2)/A = F_2^N(x,Q^2) + g_2(A,\Lambda) f_2(x,Q^2,\Lambda).$$

$$g_2(A,\Lambda) = \underbrace{\frac{1}{A}\langle A|\left(N^\dagger N\right)^2|A\rangle_\Lambda}_{\text{The contact...}}$$

$$a_2(A, x>1) = \frac{g_2(A,\Lambda)}{g_2(2,\Lambda)}$$

[SRC Scaling Factor]



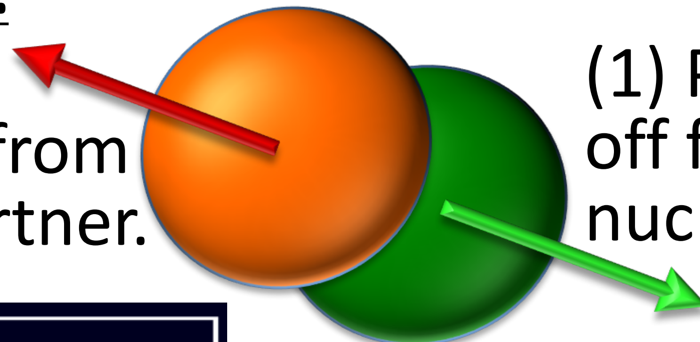
SRC Scaling factors

Tagged Structure Functions (JLab12)

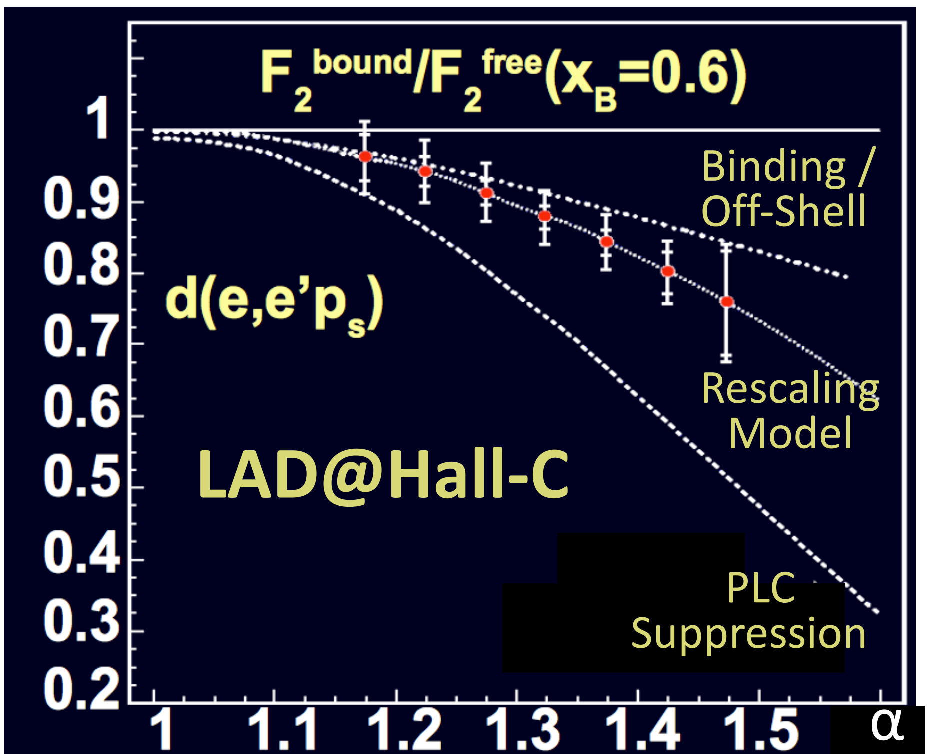
Internal structure of SRC nucleons?

Focus on the deuteron:

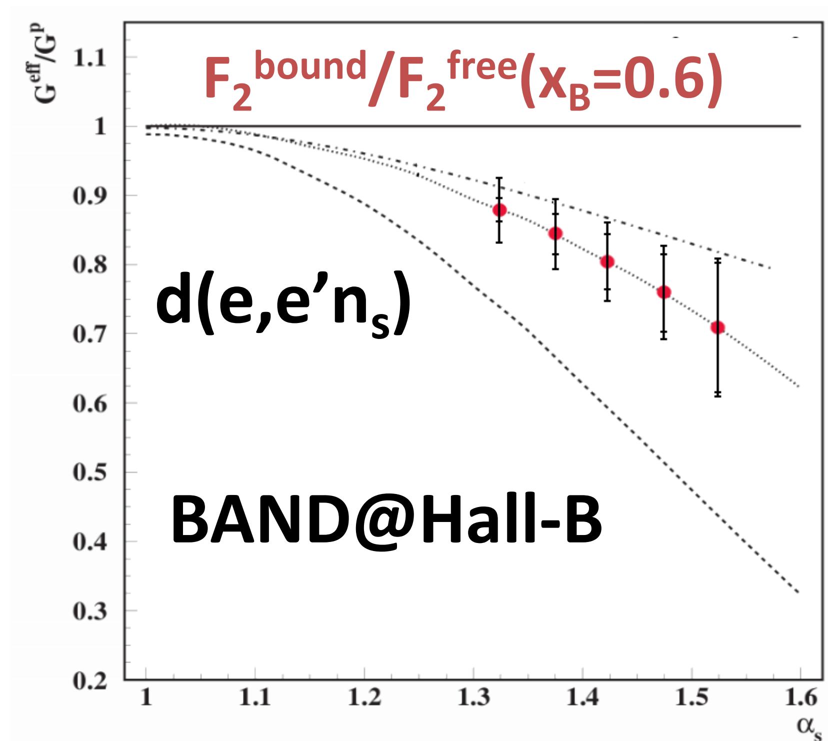
(2) Infer its momentum from the recoil partner.



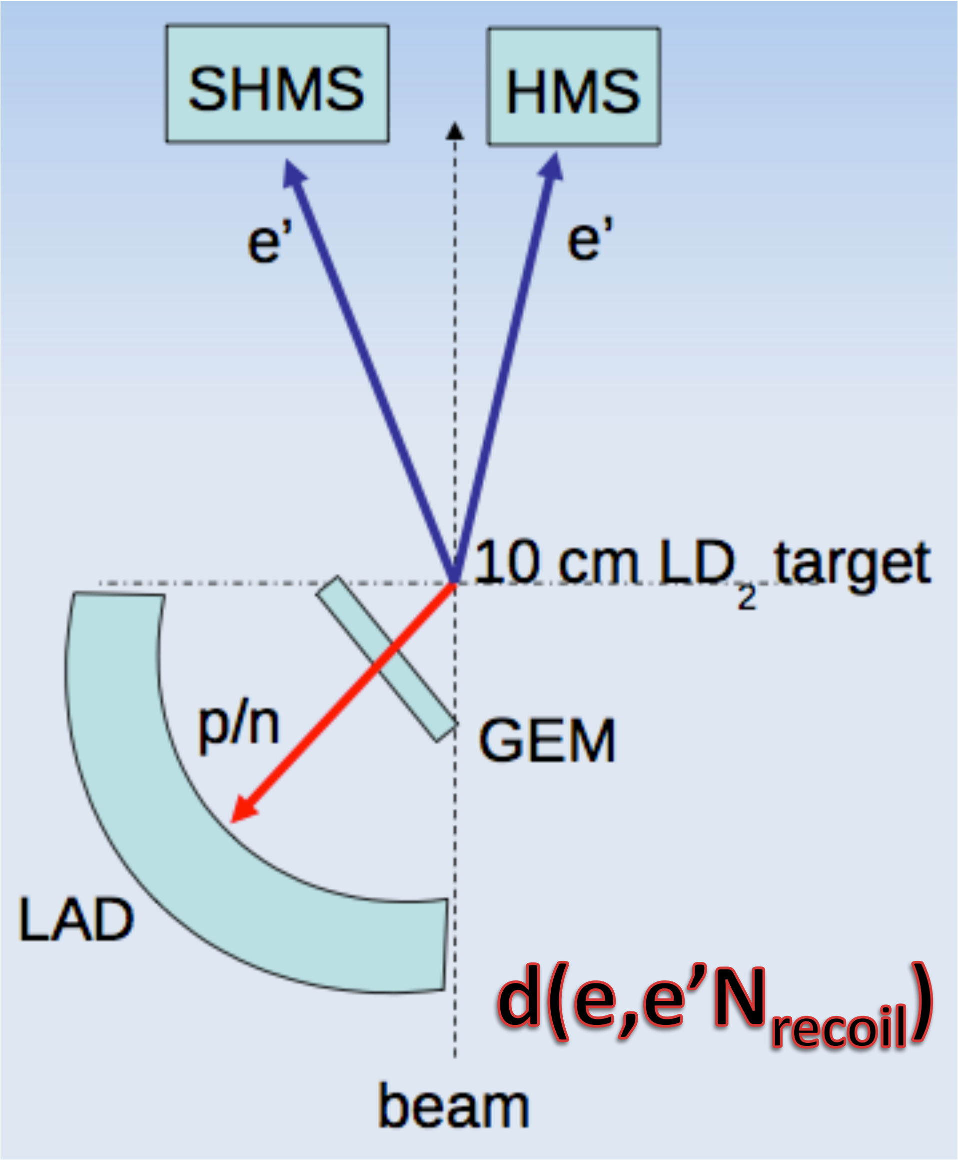
(1) Perform DIS off forward going nucleon.



Melnitchouk et al., Z. Phys. A **359**, 99-109 (1997)



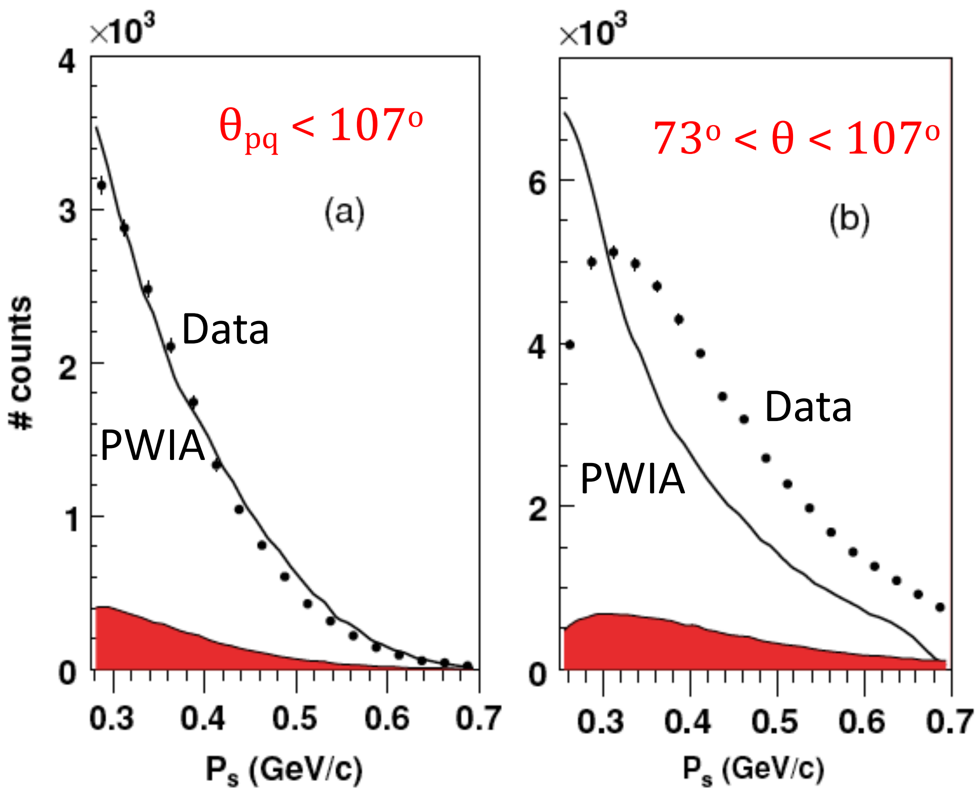
Fixed Target Concept…



- High resolution spectrometers for d(e,e') measurement in DIS kinematics
- Large acceptance recoil proton \ neutron detector
- Long target + GEM detector – reduce random coincidence

Backward Kinematics: Minimize Re-Scattering

D(e,e'p_S)

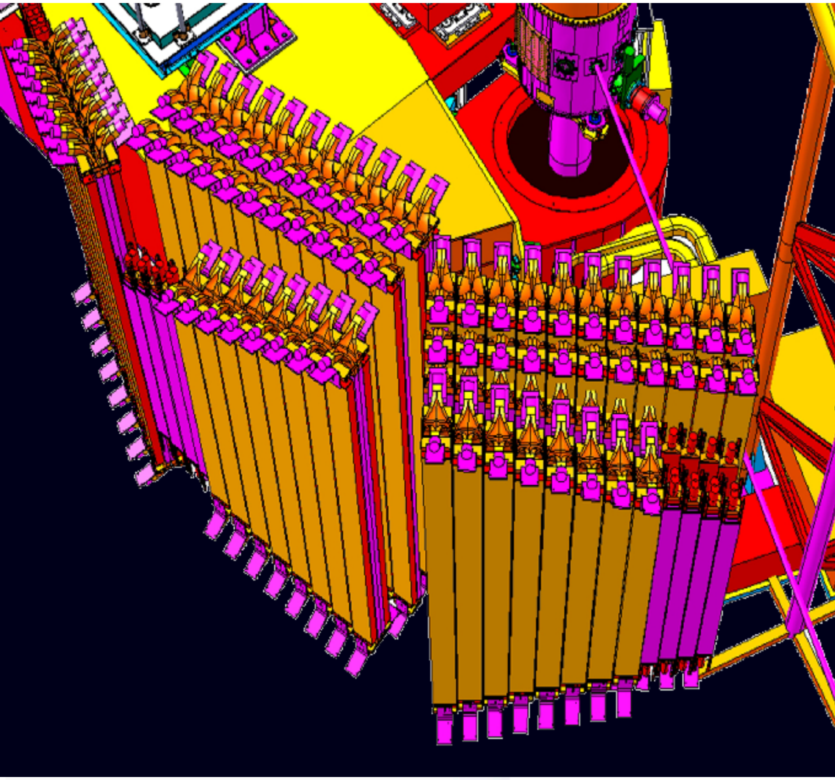


FSI:

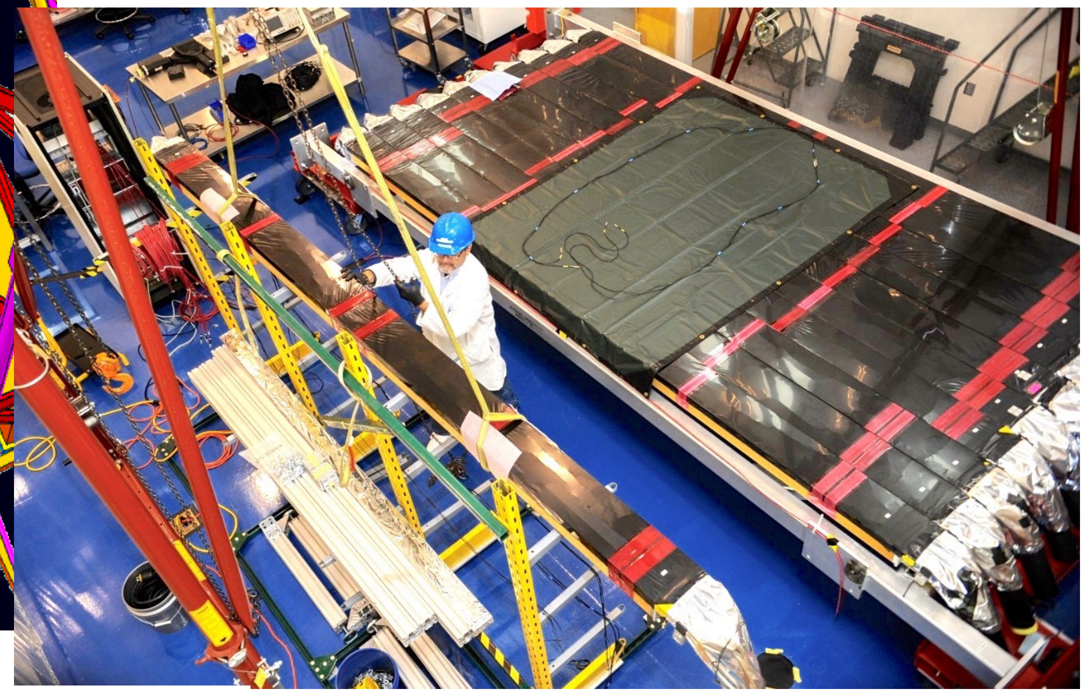
- Decrease with Q^2
- Increase with W'
- Not sensitive to x'
- Small for $\theta_{pq} > 107°$

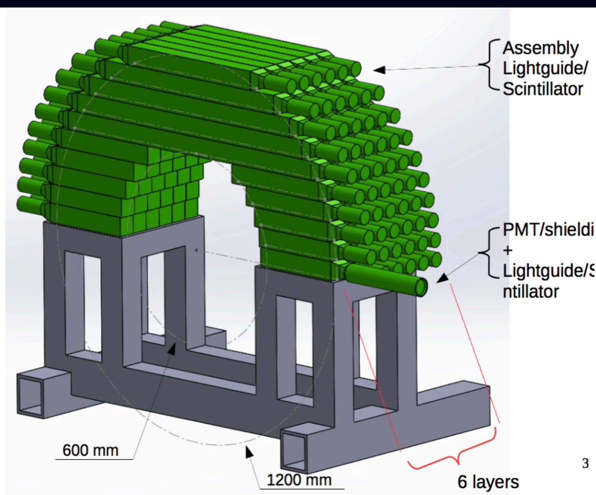
A. V. Klimenko *et al.*, PRC **73**, 035212 (2006)

Next Generation Experiments

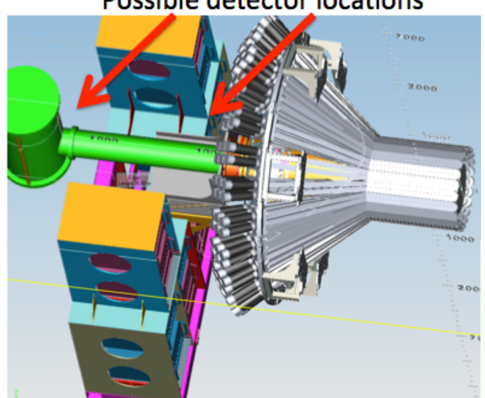


Large Acceptance Detector (LAD@Hall-C)





Possible detector locations

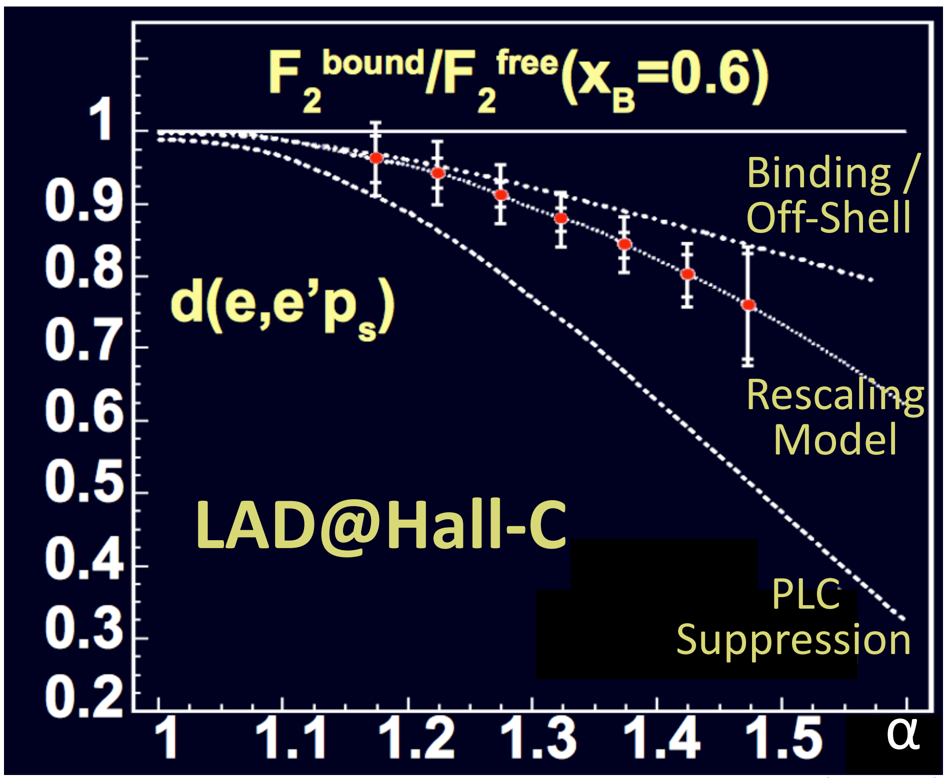


Backward Angle Neutron Detector (BAND@Hall-B)

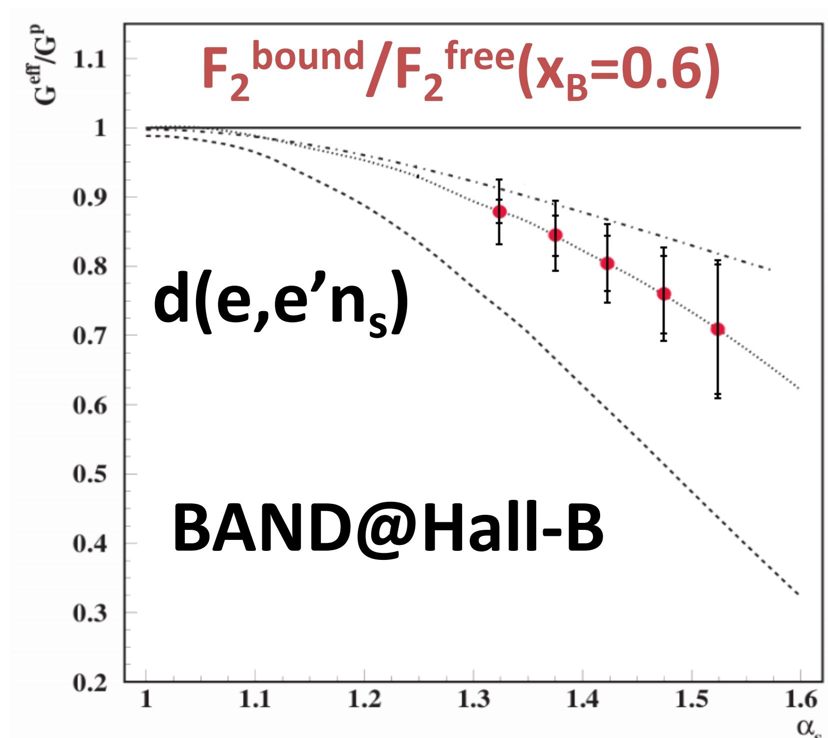
R&D @ MIT / Construction @ BATES

Kinematics and Uncertainties

- Tagging allows to extract the structure function in the nucleon reference frame: $x' = \frac{Q^2}{2(\overline{q} \cdot \overline{p})}$
- Expected coverage: x' ~ 0.3 & 0.45(0.5) < x' < 0.55(0.7) @ $W^2 > 4$ $[GeV/c]^2$



Melnitchouk et al., Z. Phys. A **359**, 99-109 (1997)

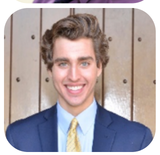


The Correlations group

- **MIT (Or Hen):**


Barak Schmookler


Reynier Torres


Efrain Segarra


Afroditi Papadopoulou

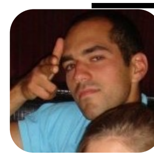

Axel Schmidt


George Laskaris

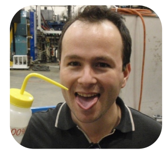

Maria Patsyuk


Taofeng Wang (*visiting scientist)

- **TAU (Eli Piasetzky):**


Erez Cohen


Meytal Duer


Igor Korover


Adi Ashkenazy

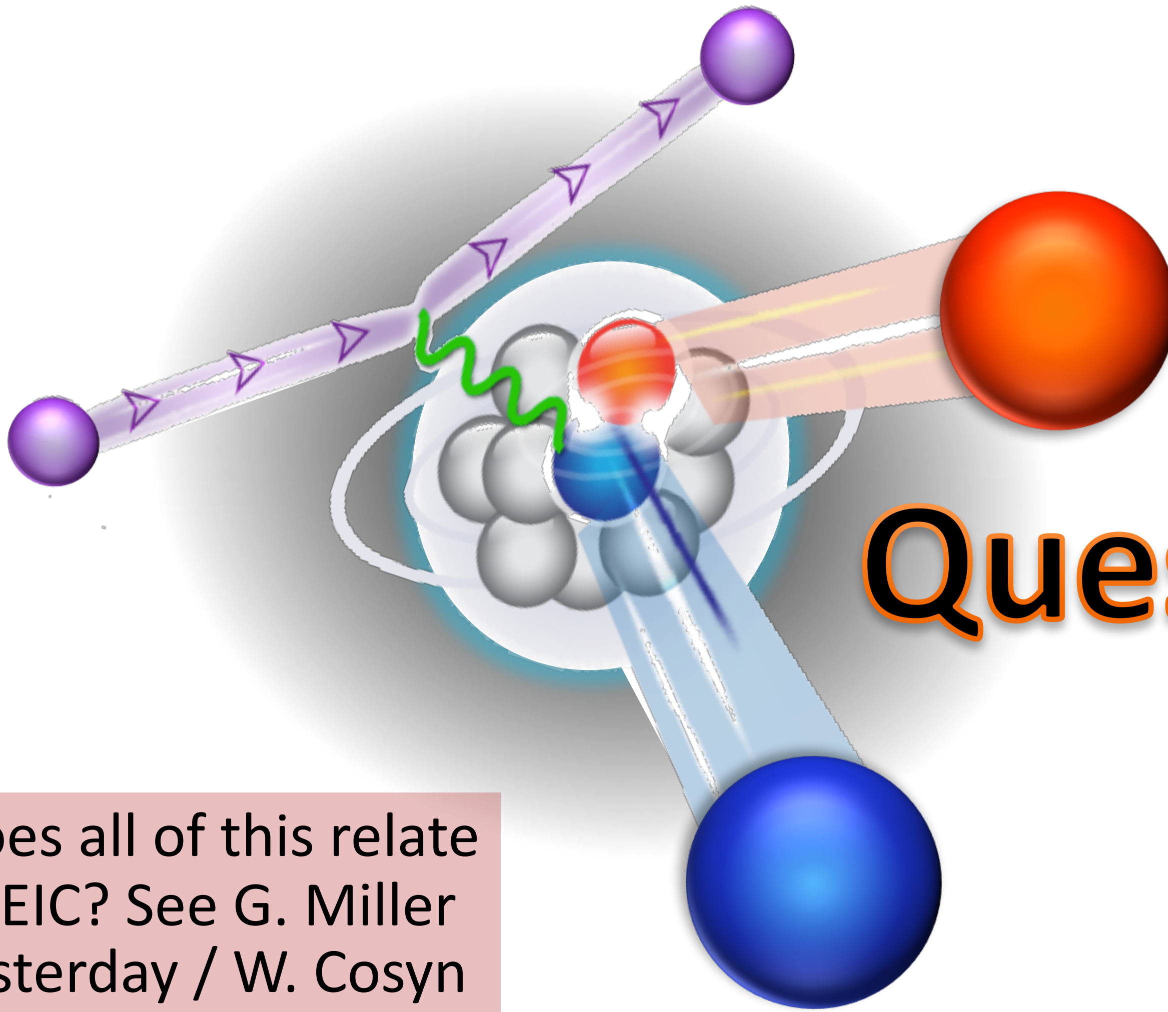
- **ODU (Larry Weinstein):**


Mariana Khachatryan


Florian Hauenstein

- **Theory Collaborators (lots!)**

Thank You!



Questions?

How does all of this relate to the EIC? See G. Miller talk yesterday / W. Cosyn talk tomorrow.